A Universe of Energy: Emerging Technologies to Expand Our Energy "ToolBox" for Planet Earth, Our Solar System, and Beyond

presented at

2018 CMOS Emerging Technologies

Energy Harvesting and Storage

Whistler, British Columbia, Canada

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AGENDA

- Recent Spacecraft Power Systems
- Terrestrial Energy Recovery Applications
  - Motivations
  - New Emerging TE Materials
  - High Power Density TE Module Technology
- High Temperature Solar Photovoltaics
- Final Thoughts

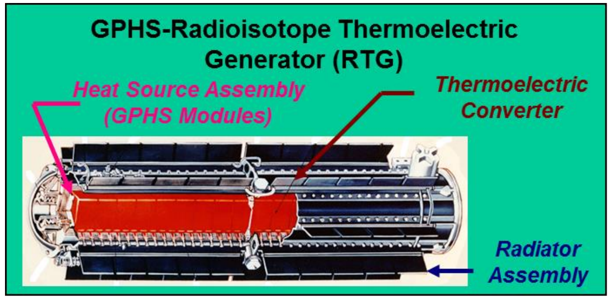
NASA Science Exploration Missions Need for Both Solar & Radioisotope Power Systems (RPS)

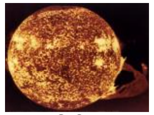
Solar power systems serve a *critical role* in the scientific exploration of the near-Earth solar system

- Moderate power levels up to 100 kW
- Operations dependent on distance and orientation with respect to Sun

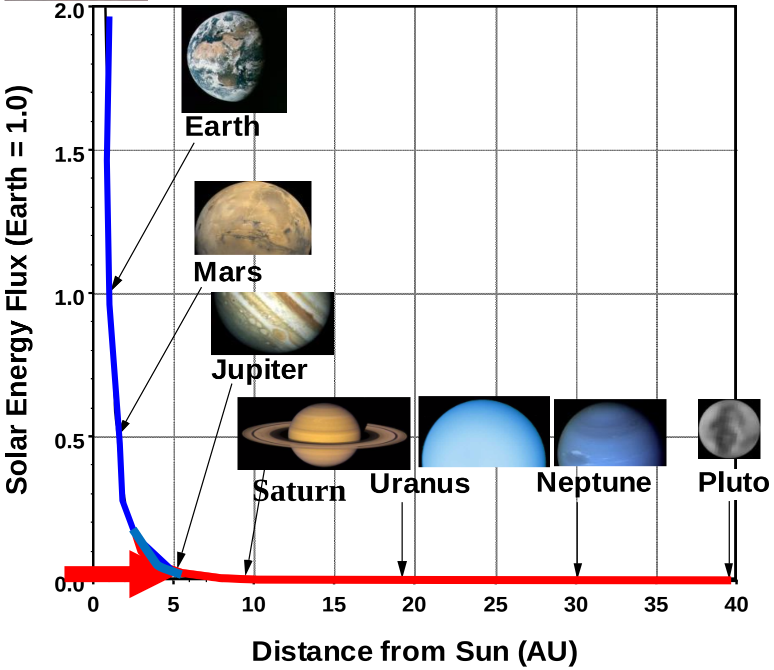
Radioisotope power systems (RPS) serve a *critical role* in the scientific exploration of the deep-space solar system

- Low to moderate power levels (~100 W - 1 kW) for more than several months
- Operations independent of distance and orientation with respect to Sun

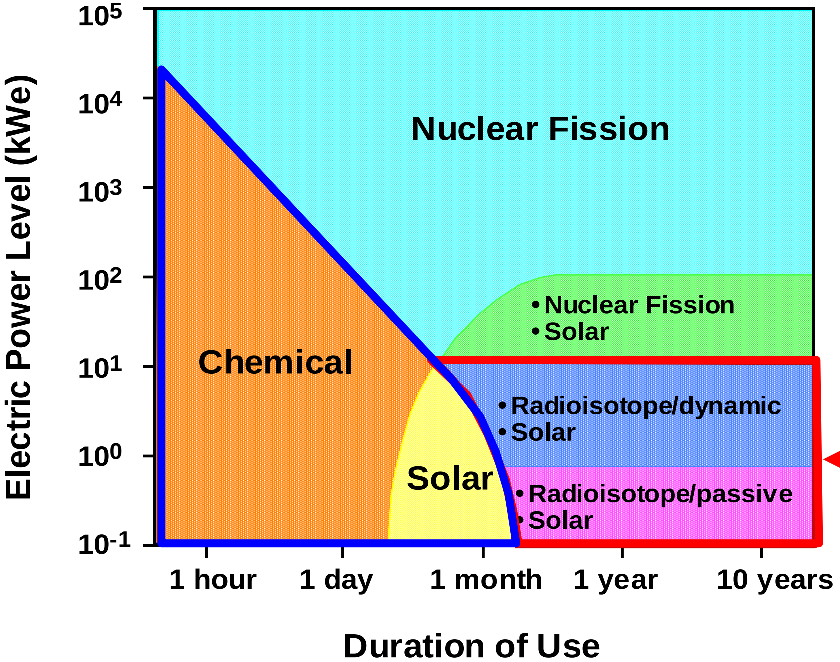


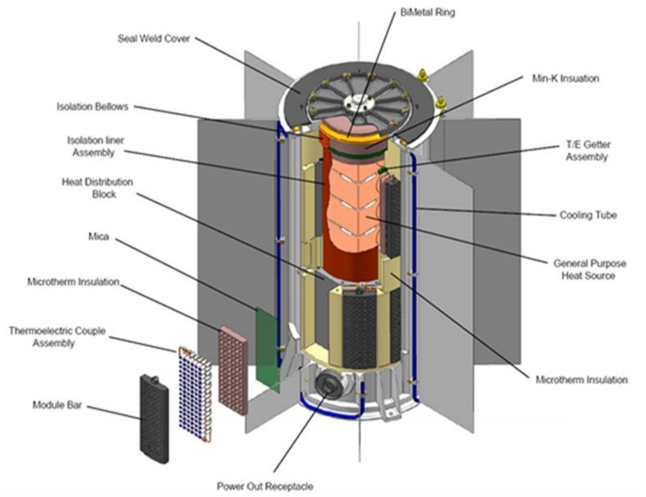


Inherent limitation of solar power



Best candidates for maximizing specific power

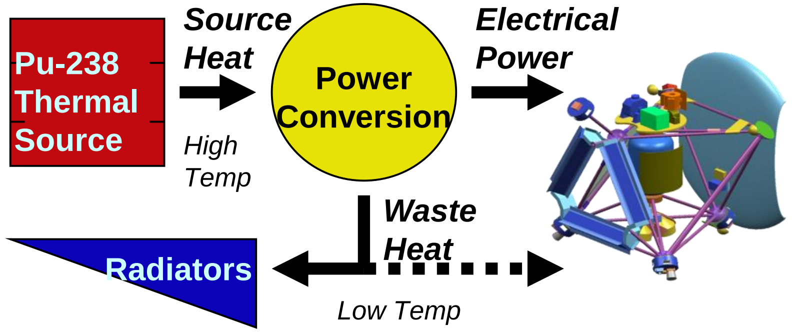




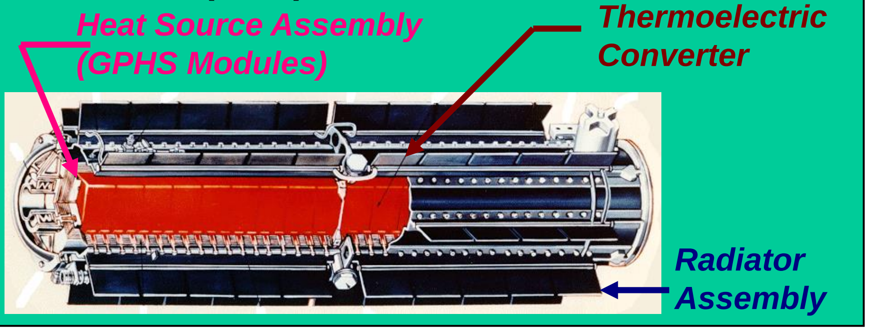
Multi-Mission RTG

Overview of a Radioisotope Power System

- **High grade heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
  - 87.7-year half-life
  - Heat source temperature ~ 1300 K
- **Portion of heat energy converted to electricity via passive or dynamic thermal cycles (6%-35%)**
  - Thermoelectric (existing & under development)
  - Stirling (under development)
  - Thermophotovoltaic, Brayton, etc. (future candidates)
- **Waste heat rejected through radiators or a portion can be used for thermal control of spacecraft subsystems**



GPHS-Radioisotope Thermoelectric Generator (RTG)



Performance characteristics

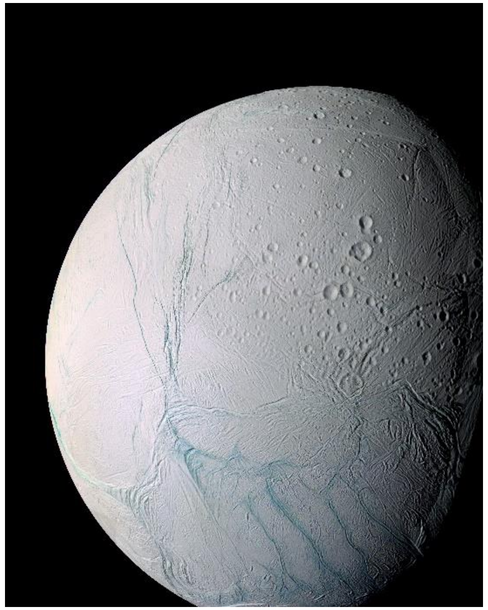
- Specific power (W/kg) $\rightarrow$ Direct impact on science payload
- T/E efficiency $\rightarrow$ Reduces PuO_2 needs
- Power output $\rightarrow$ Supports diverse mission profiles

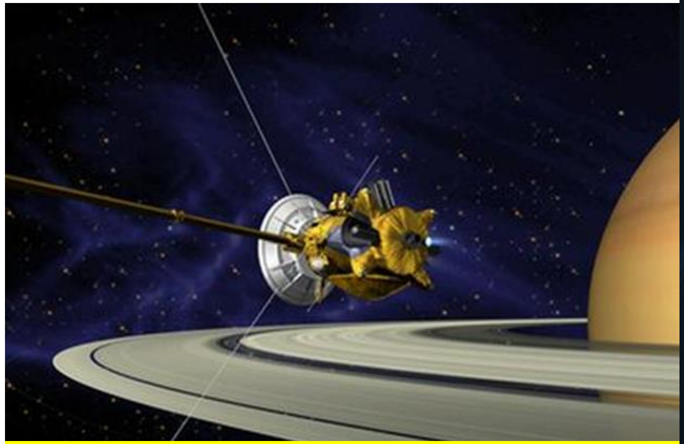
RTGs used successfully on 27 spacecrafts since 1961

- 11 Planetary (Pioneer 10 & 11, Voyager 1 & 2, Galileo, Ulysses, Cassini, New Horizons)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP), 3 Mars Surface (Viking, MSL/Curiosity)

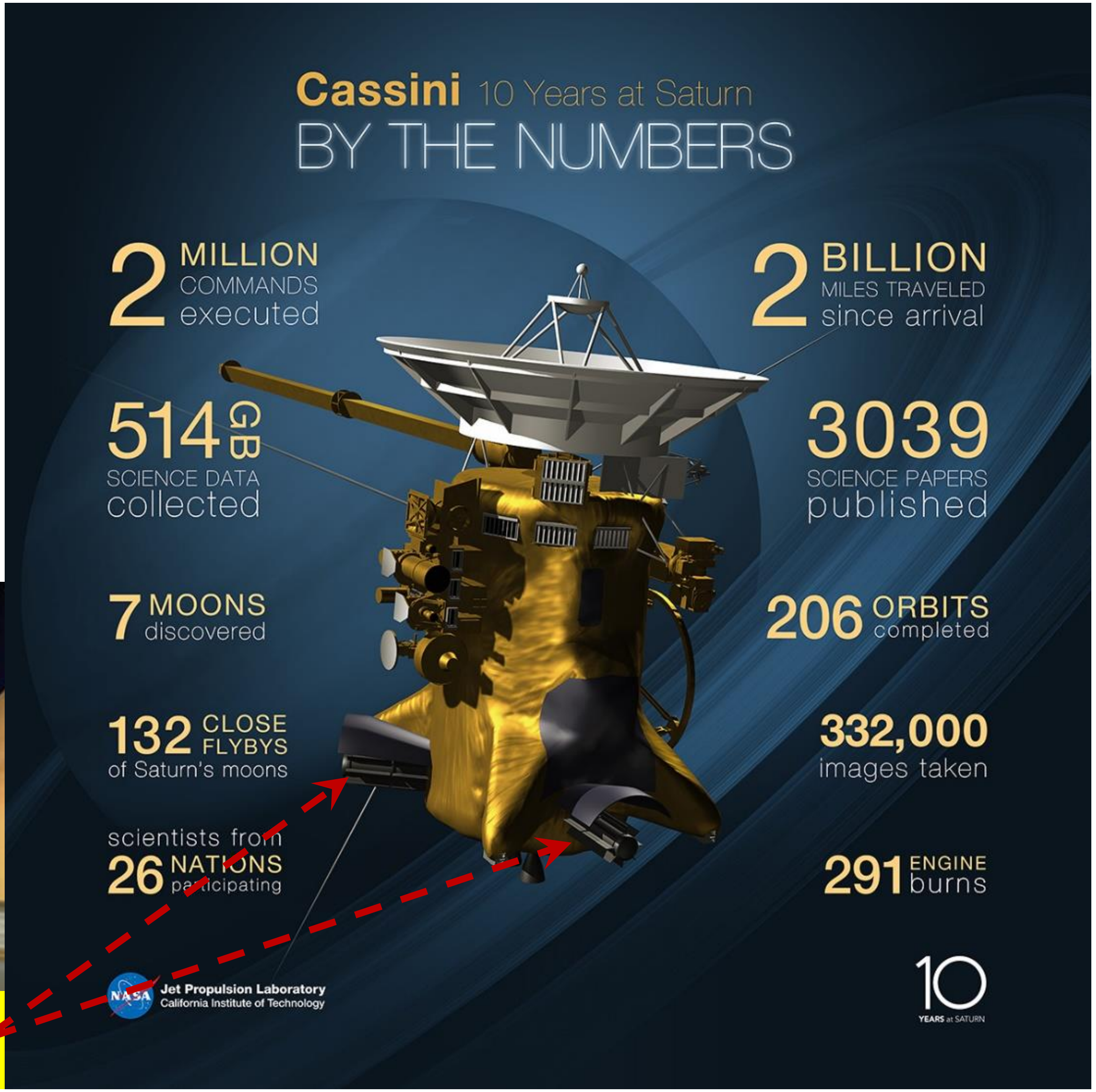
CASSINI Spacecraft to Saturn (October 15th, 1997 to September 15th, 2017)

- Vastly Updated Science on Saturn's Rings
- Incredible Science on Saturn's Moon Titan
  - **Many Earth-Like Processes**
  - Liquid Rivers & Lakes of Ethane & Methane Over Frozen Water
  - Salty Brine Ocean Under Icy Crust
  - Liquid Water and Ammonia Ocean ~100km Below Frozen Crust
- Likewise, Saturn's Moon Enceladus
  - **Liquid Water Beneath its Icy, Snowy Crust**
  - Geologic Activity – Ice & Water Crystal Plumes at its South Pole



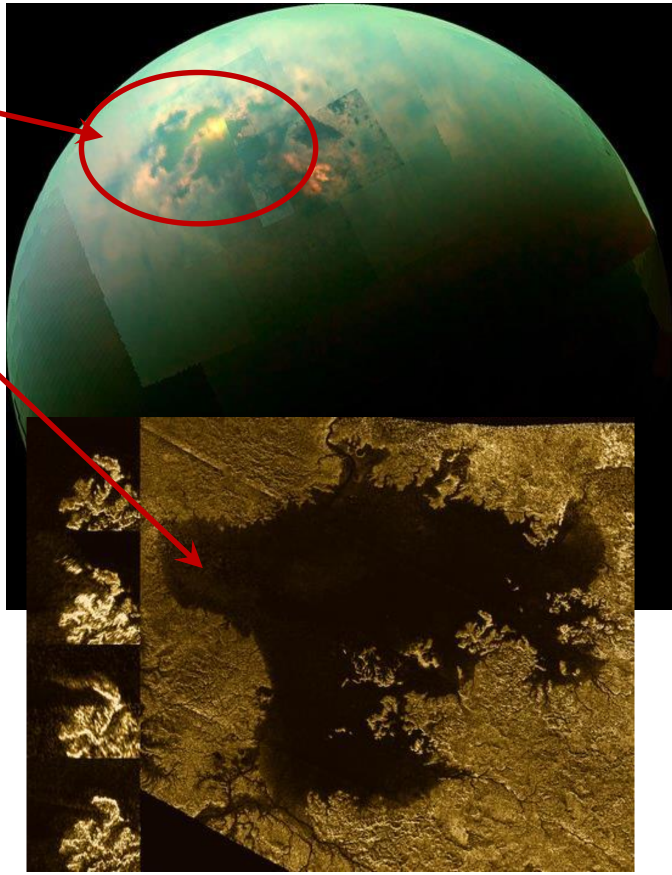


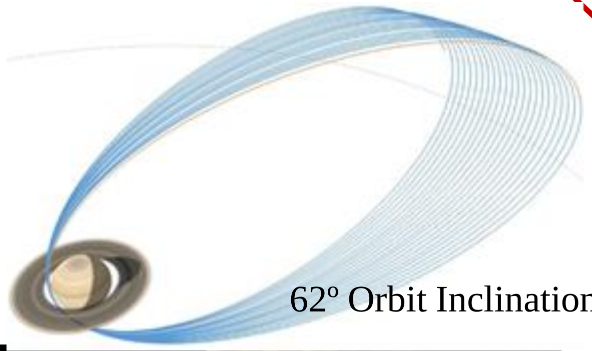
RTG Power Made this All Possible
SiGe TE Materials



CASSINI Spacecraft to Saturn (1997-2017)

- Liquid Rivers & Lakes of Ethane & Methane Over Frozen Water
  - Ethane and Methane “Rains” in Atmosphere (Pressure Slightly Higher than ~1 atm)
  - Methane Atmosphere ~5% Methane – Geologic Processes Replacing Methane
- Flew Cassini spacecraft into Saturn on 15 September 2017 (Final Dive)
  - **Grand Finale** - 22 passes between ~2500-km gap between inner rings / Saturn’s upper atmosphere
  - Velocity during inner ring passages 121,000-126,000 kmph
  - RTG Power Degradation shown below – 32% over 20 years
  - Lost Cassini signal 1400 km above clouds





62º Orbit Inclination

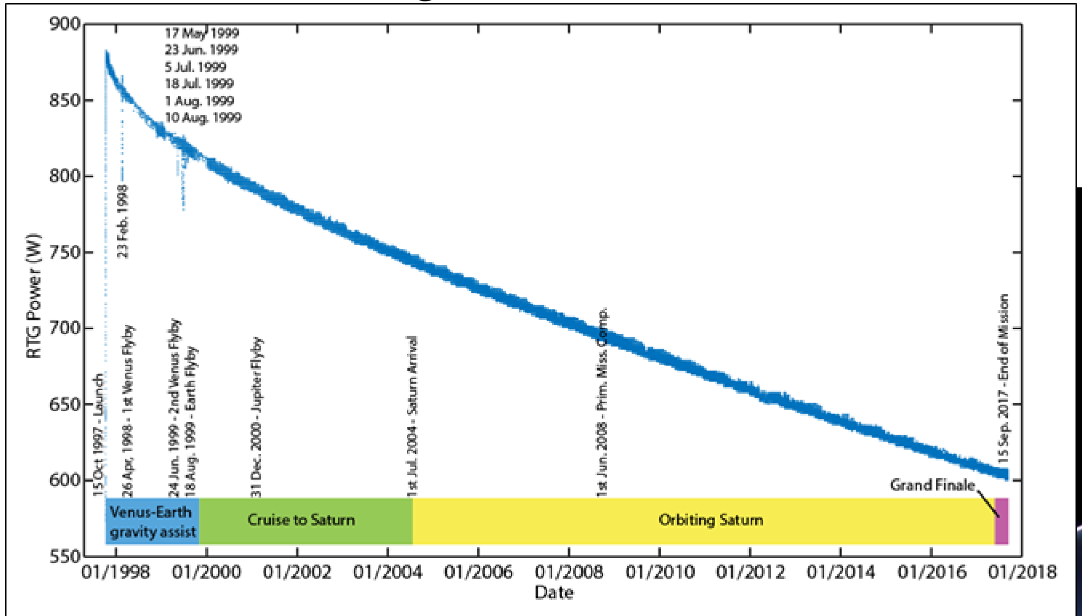


Fig. 1. Cassini recorded power output telemetry data over the entire mission between launch and EOM. The data is divided into four mission phases: The Venus-Earth gravity assist, the cruise to Saturn, orbiting Saturn

RTG Power Made this All Possible
SiGe TE Materials

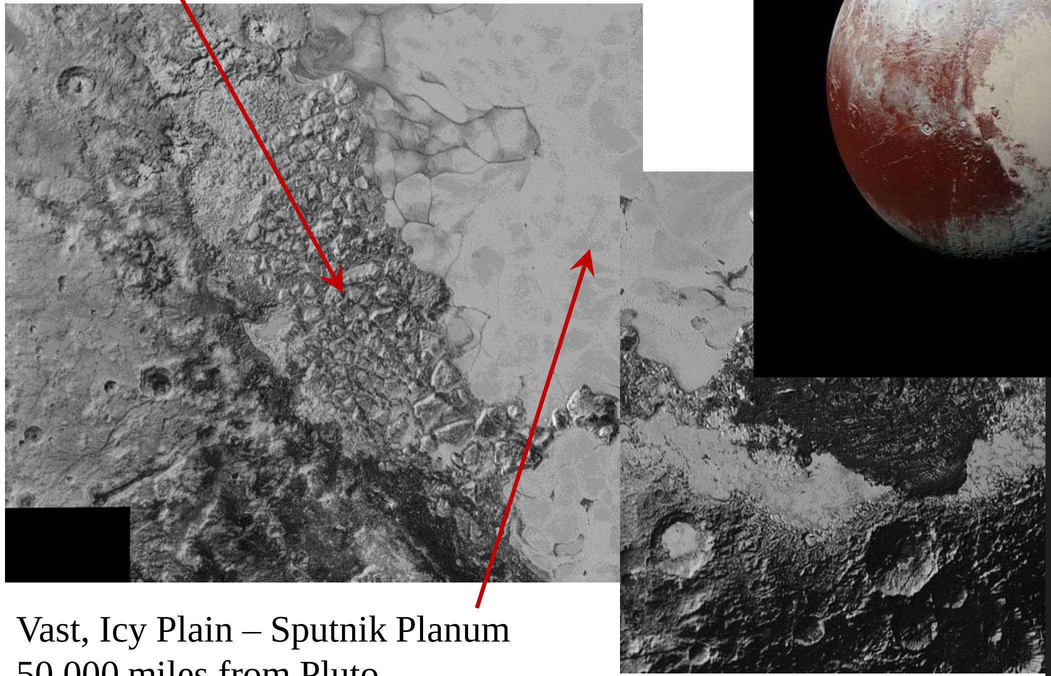
New Horizons to Pluto (2006-Continuing)

Heart of Pluto

With Love,
Pluto

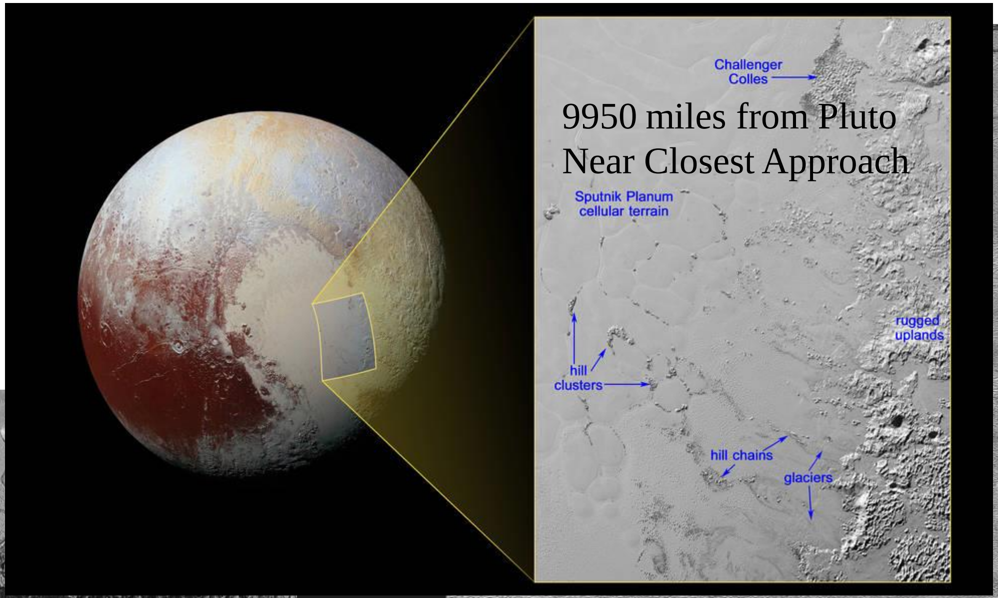
476,000 miles from Pluto

Large region of jumbled, broken terrain

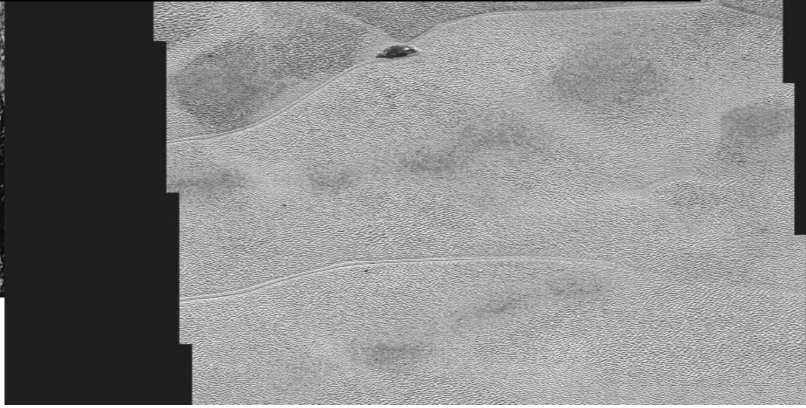


Vast, Icy Plain – Sputnik Planum
50,000 miles from Pluto

300 mile wide image, smallest features 0.5 mile wide



9950 miles from Pluto
Near Closest Approach



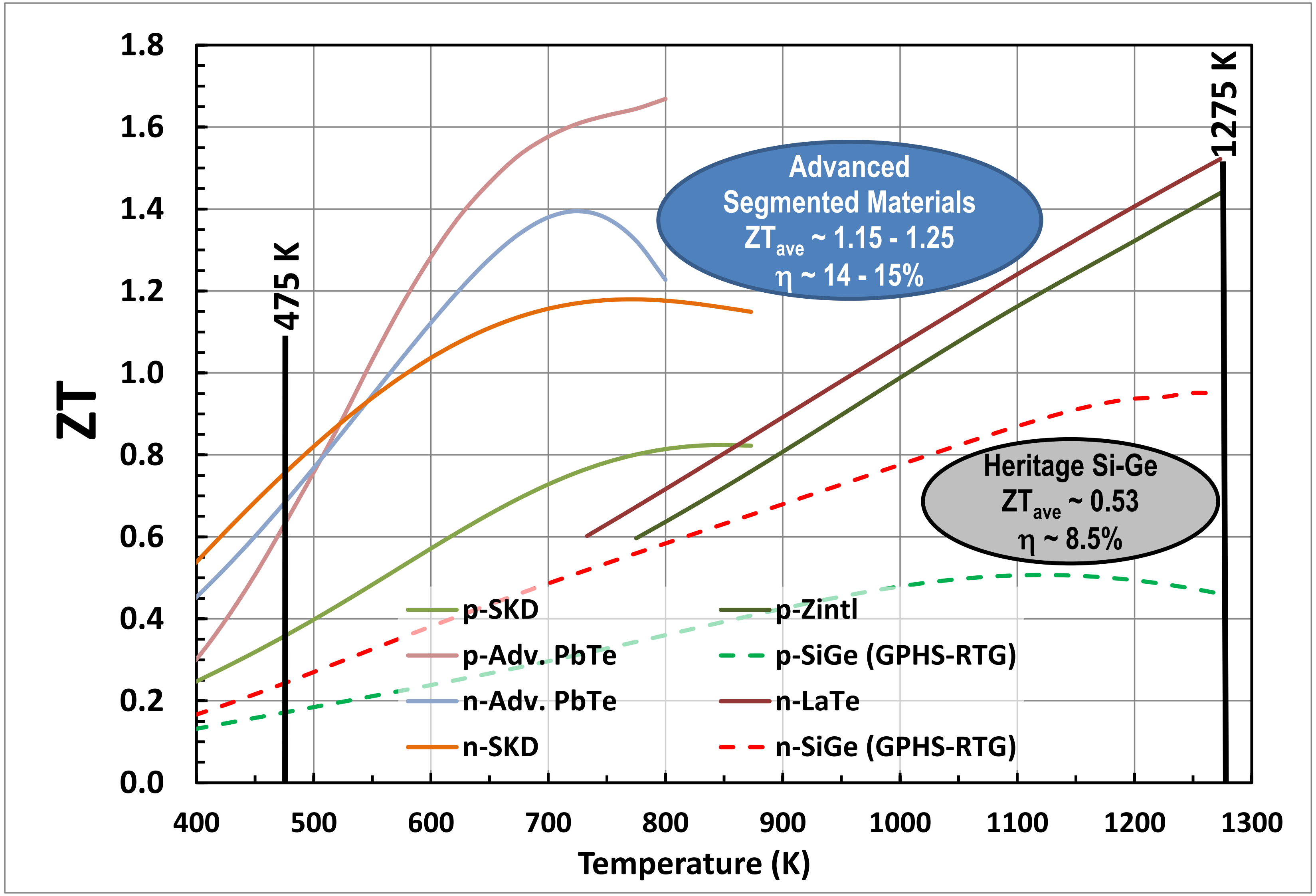
10,000 miles from Pluto

Water ice hills are floating in a sea of frozen Nitrogen

RTG Power Made this All Possible
SiGe TE Materials

New Generation of "Mature" Advanced TE Materials

Large performance gains over heritage PbTe & Si-Ge alloys



Next Generation RTG TE Technologies – Phase Space

Device Technologies

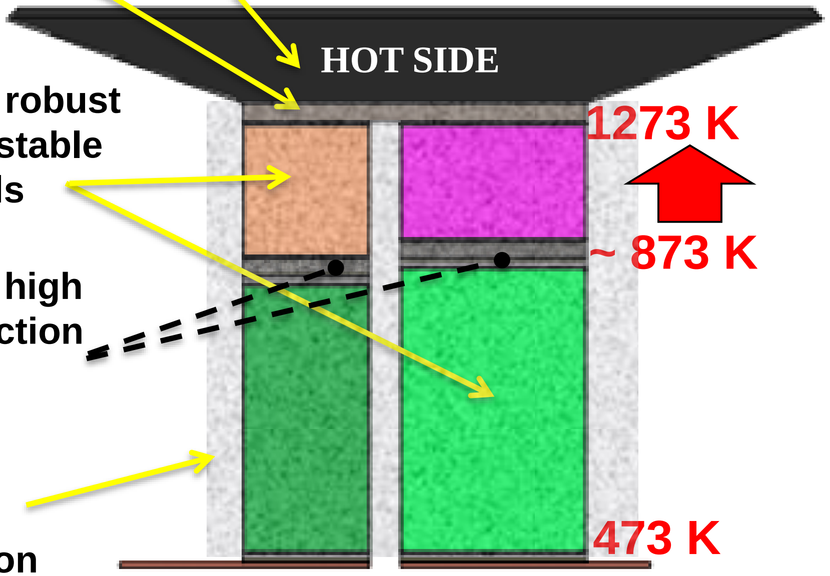
Mechanically robust & chemically stable, low contact resistance hot side metallizations

Long term stability of hot shoe

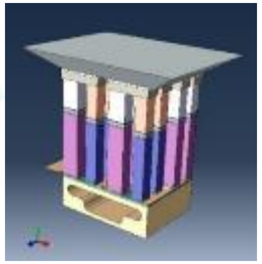
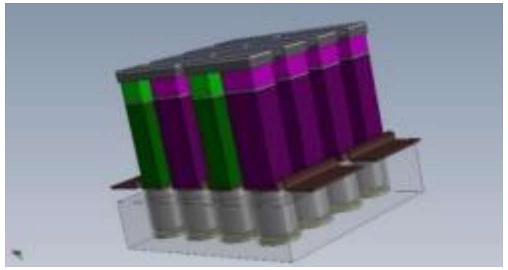
Mechanically robust & thermally stable materials

Mechanically compliant, high electrical/thermal conduction segment interfaces

Practical, effective thermal insulation / sublimation suppression



Devices:
Design, Performance testing and modeling

Materials

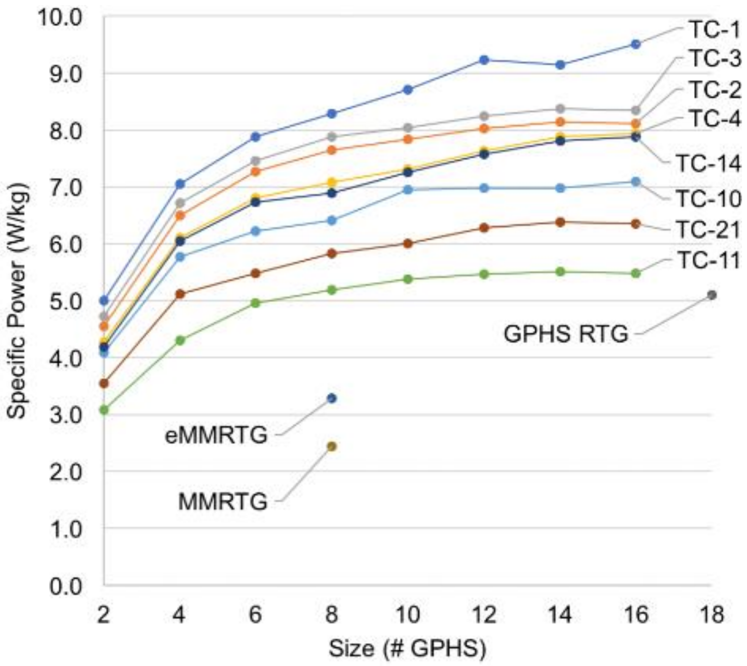
- Advanced complex materials
  - Zintls
    - 14-1-11
    - 1-2-2
    - 9-4-9
  - Chalcogenides
    - $La_{3-x}Te_4$ and other alkaline/rare earth compounds
    - Bi_2Te_3 and PbTe-based advanced materials
  - Skutterudites
  - Half-Heusler
  - Silicides
  - Tetrahedrite
- Advanced materials and interfaces
  - Opacified aerogels
  - Composites

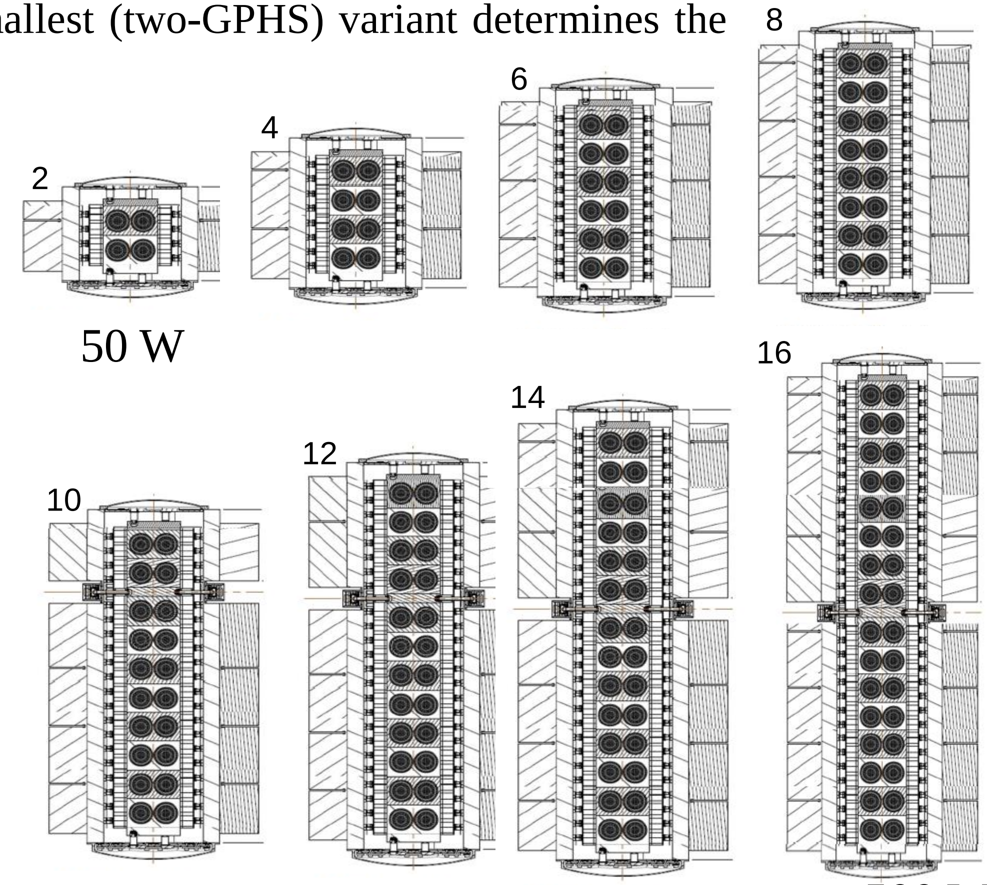
LaTe composites have starting particle sizes of 80 nm – 150 nm range, and after synthesis process it increases to submicron – 10’s of microns in finished bulk

Next-Generation RTGs for NASA – *Concepts*

- Types of *new* RTG Concepts:
  - Vacuum Only
    - Segmented (TECs)
    - Cold Segmented
    - Segmented-Modular
    - Cold Segmented-Modular
  - Vacuum and Atmosphere
    - Hybrid Segmented-Modular
    - Cold Hybrid Segmented-Modular
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS
  - Output Voltage ~34 Vdc

- Typically, NASA spacecraft power busses have been designed to operate in the range of **22 to 36 V**.
- A two-GPHS unit was determined to be the **smallest SMRTG variant** capable of supporting the necessary number of TECs to meet the specified voltage requirement.
- This basic architecture would be electrically **integrated in parallel** for larger variants, such that the smallest (two-GPHS) variant determines the output voltage.

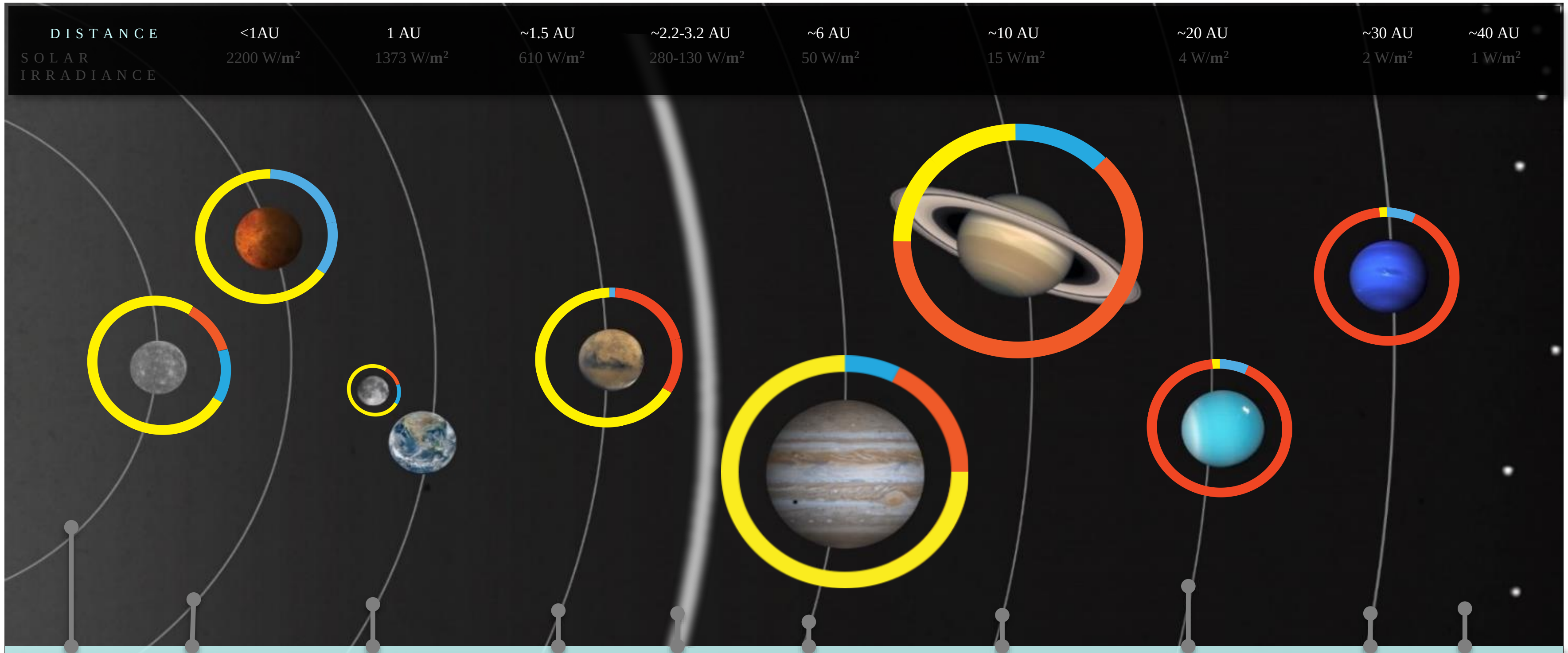




500 W

Pre-Decisional Information -- For Planning and Discussion Purposes Only

POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015[(1)]



MERCURY

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS

SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS

SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER

SOLAR
- Orbiters
- Flybys

RPS
- High capability
- orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN

SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys

BATTERIES
- Atmospheric probes

NEPTUNE

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

Solar
RPS
Primary Battery

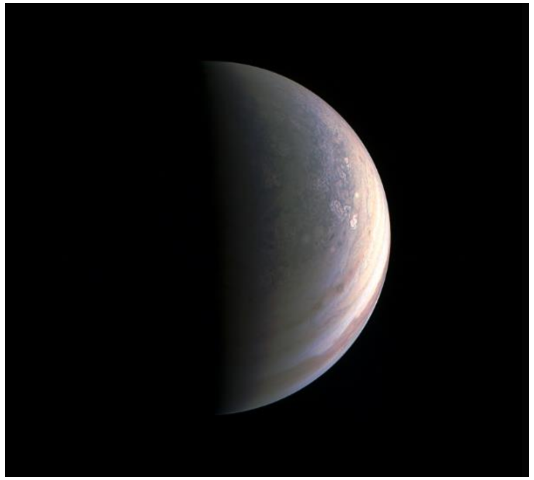
(1) *Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015*

SPACECRAFT SOLAR SYSTEMS
DAWN & JUNO Missions

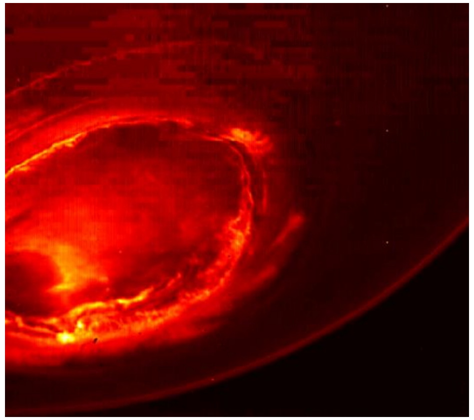
- Dawn Spacecraft
  - Asteroid Chasing - Vesta and Ceres Asteroids
  - Hyper-efficient Ion-Propulsion (Xenon fueled)
  - 10 kW of Solar Power @ 1 A.U.; 1.3 kW @ 3 A.U.
  - InGaP/InGaAs/Ge Triple Junction PV Cells (35.4 m^2)
  - Low Intensity, Low Temperature PV Effects Considered (Emerging)
- Juno Spacecraft
  - Launched to Jupiter in July 2011; Arrived July 2016
  - InGaP/InGaAs/Ge Triple Junction PV Cells
  - 256 sq. ft. (23.8 m^2) per array, 3 arrays
  - Study Jupiter Atmosphere, Magnetic, & Gravity Fields
  - H_2O and NH_3 Measurements in Atmosphere

Latest From Juno @ Jupiter

- North Pole of Jupiter – 2500 miles Above Clouds
- Notice Absence of Banded Cloud Structure



- Deep in Jupiter's atmosphere, under great pressure, H_2 gas is squeezed into fluid known as metallic hydrogen
- At these enormous pressures, the H_2 acts like an electrically conducting metal
- Believed to be the source of the planet's intense magnetic field
- Powerful magnetic environment creates the brightest auroras in our solar system, as charged particles precipitate down into the planet's atmosphere.
- Juno will directly sample the charged particles and magnetic fields near Jupiter's poles for the first time



Southern Aurora 2500 miles above clouds

Latest From Juno @ Jupiter

- Jupiter pictures during the Juno orbit as it swings in and swings out in elliptical orbit

- This is its first arrival and departure in e-orbit

- More information at:

  http://www.jpl.nasa.gov/news/press_kits/juno/science/

Imagine, Innovate, “Instigate” to Real-World Applications

1

39,000 m Up at Edge of Space
Mach 1.25

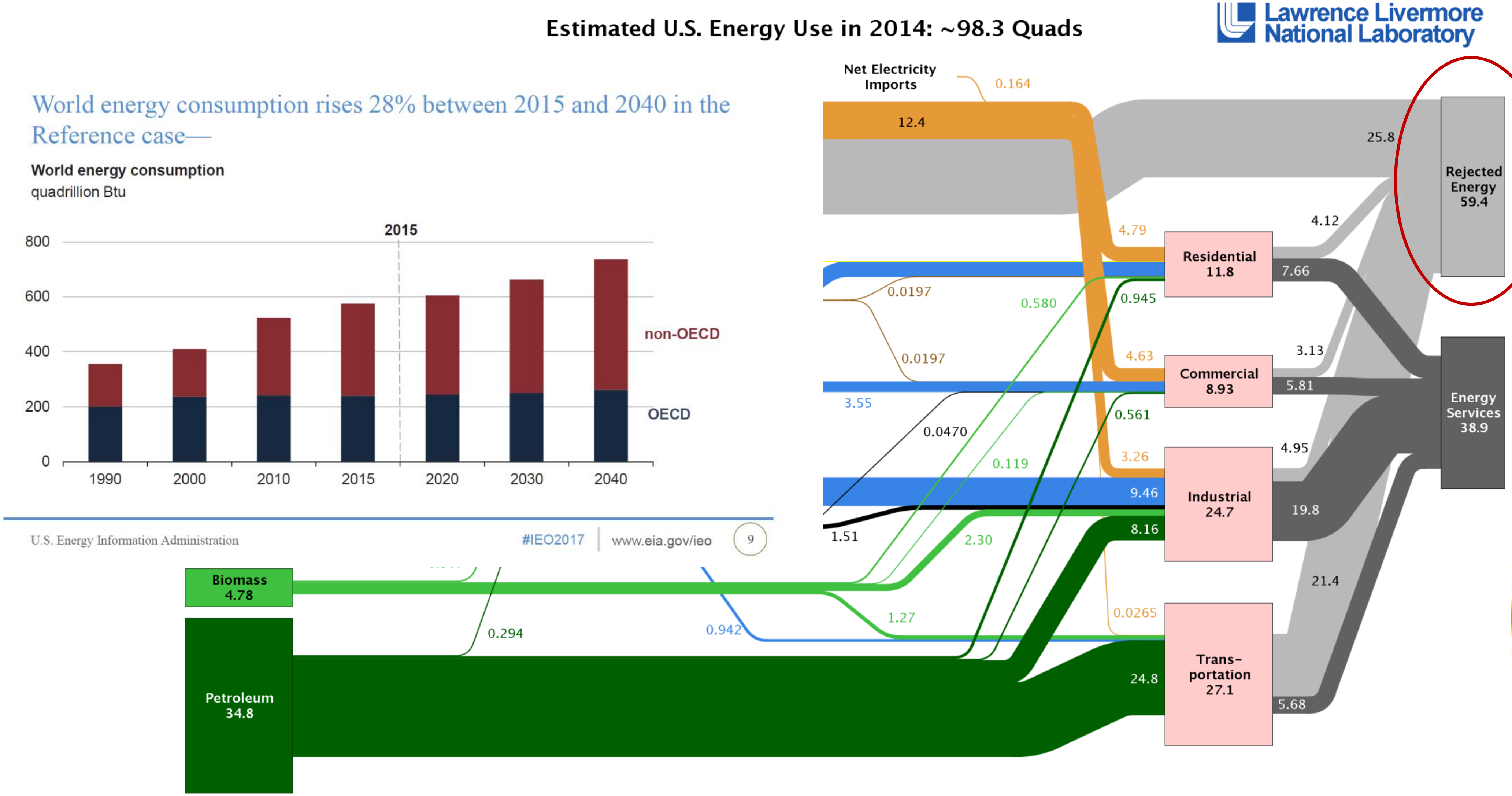
Looks Like Space to Me!!

1

So Talking About Dual-Use Technologies …..

[1] http://en.wikipedia.org/wiki/Felix_Baumgartner
http://www.youtube.com/watch?v=FHtvDA0W34I

United States Energy Flow



- Waste Heat To Be "Harvested"

 59.4 Quads

- Up ~ 5Quads From 2009

Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

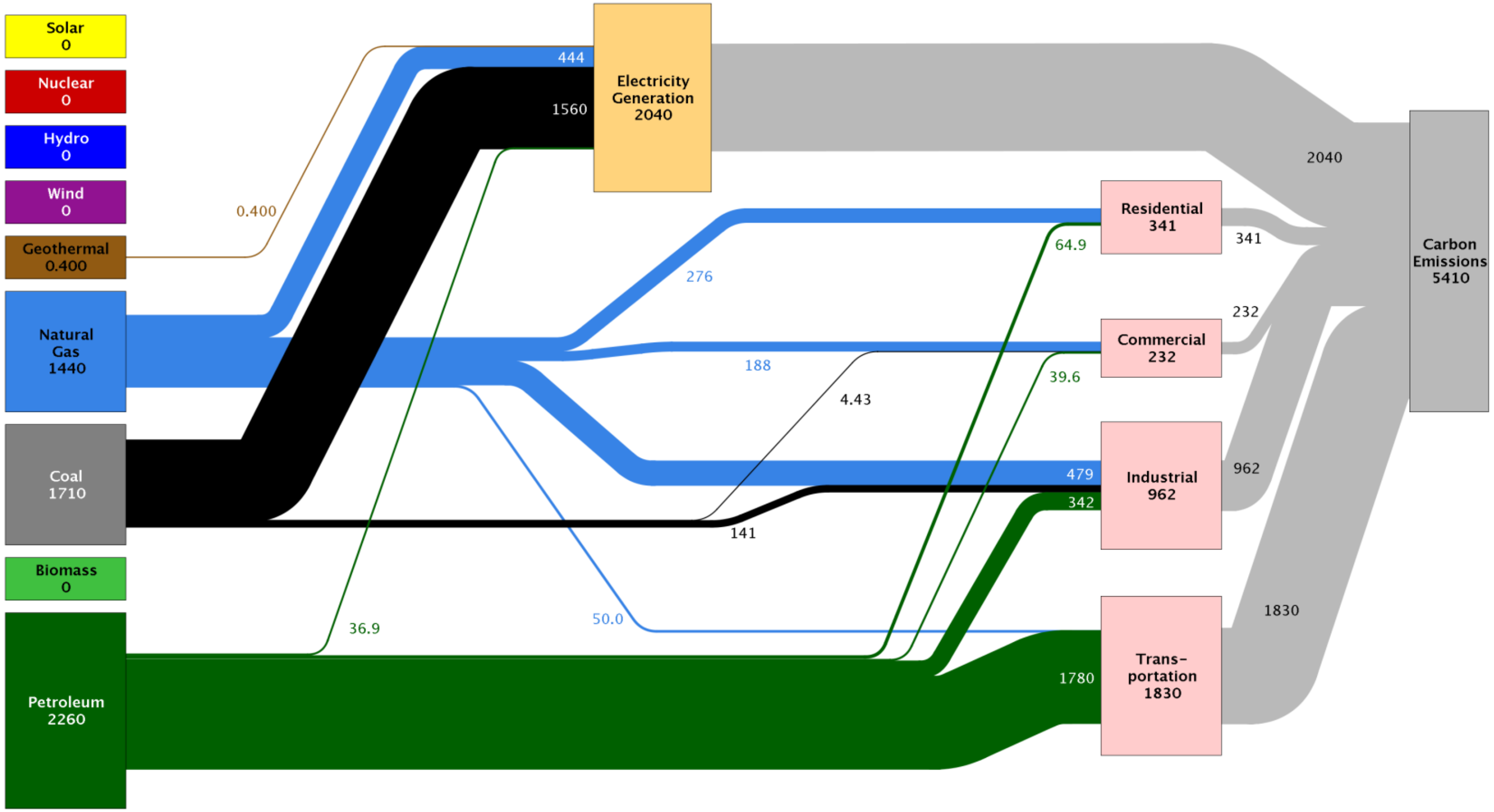
Environmental Effects Are Strongly Tied to Our Energy Use

- ~1 kg of CO_2 produced per 1 kWhr (Coal Produced Power)
- ~0.5 kg of CO_2 is produced for 1 kWhr (Natural Gas Power)

Down ~400 Million Metric Tons From 2008
Mostly from Reduced Coal & Petroleum Use

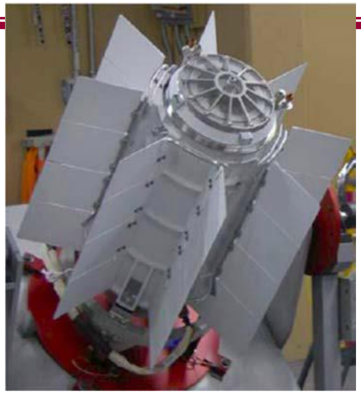
Estimated U.S. Carbon Emissions in 2014: ~5,410 Million Metric Tons

Lawrence Livermore National Laboratory

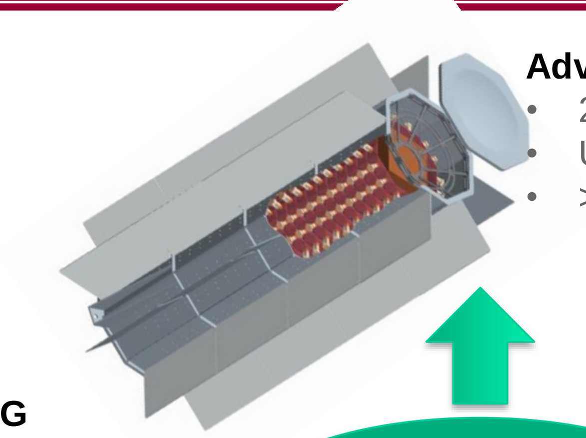


Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2015. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Carbon emissions are attributed to their physical source, and are not allocated to end use for electricity consumption in the residential, commercial, industrial and transportation sectors. Petroleum consumption in the electric power sector includes the non-renewable portion of municipal solid waste. Combustion of biologically derived fuels is assumed to have zero net carbon emissions – the lifecycle emissions associated with producing biofuels are included in commercial and industrial emissions. Totals may not equal sum of components due to independent rounding errors. LLNL-MI-410527

Potential Near Term Space & Terrestrial Applications for Advanced TE Power Systems

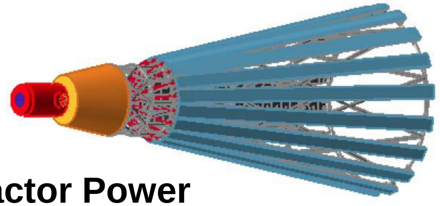


Early 2020's



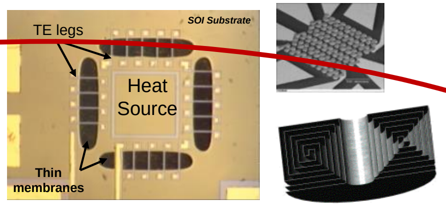
Advanced RTG Concepts
- 200-500 W
- Up to 8.6 W/kg
- > 11% efficiency

Late 2020's



Fission Reactor Power System Concepts
- 0.5 to 10's of kW-class

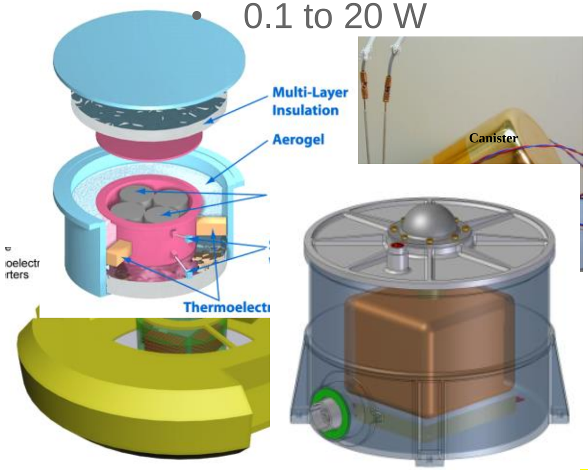
Energy Harvesting
- Miniaturized devices
- Extreme environments



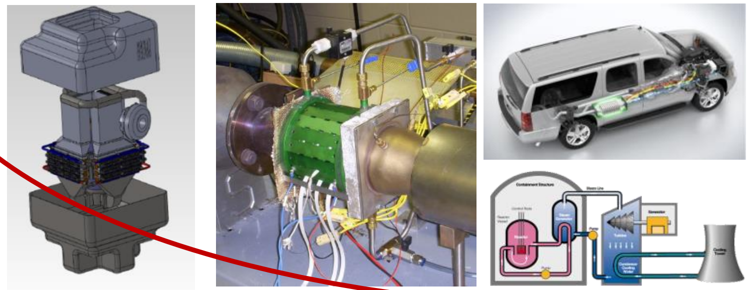
Advanced TE Technology

Proposed Enhanced MMRTG
- ~ 160 W
- ~ 3.8 W/kg
- ~ 8% efficiency

Small RTGs Concepts
- 0.1 to 20 W



Auxiliary and waste heat recovery power systems



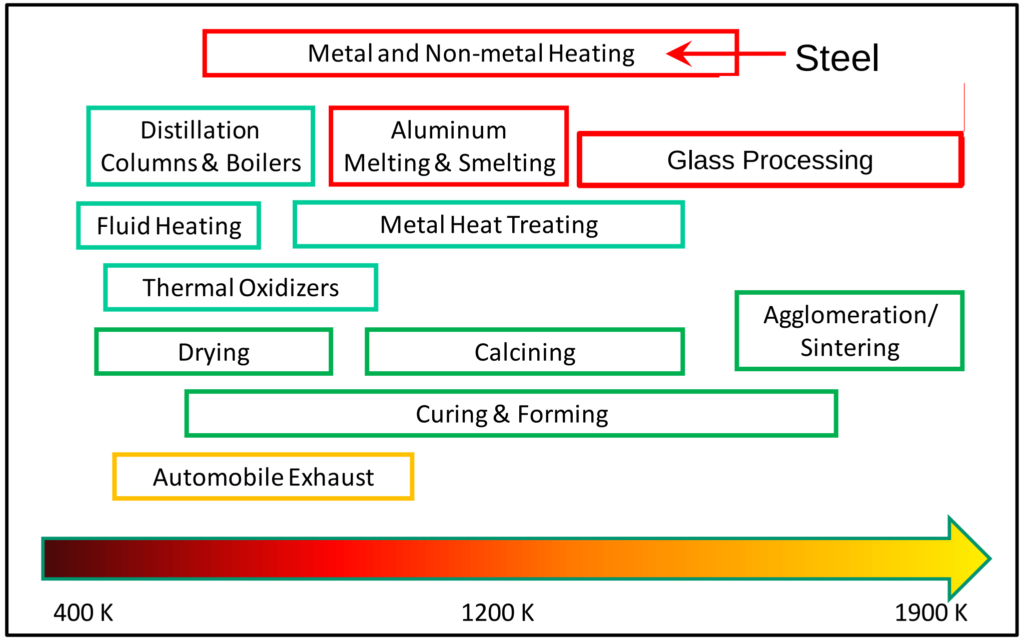
Power Plants

Large Scale Industrial Applications

RTG space power system technology and advanced high temperature TE technology can be applied across a wide spectrum of terrestrial and space power applications

Industrial Process Energy Recovery Projects

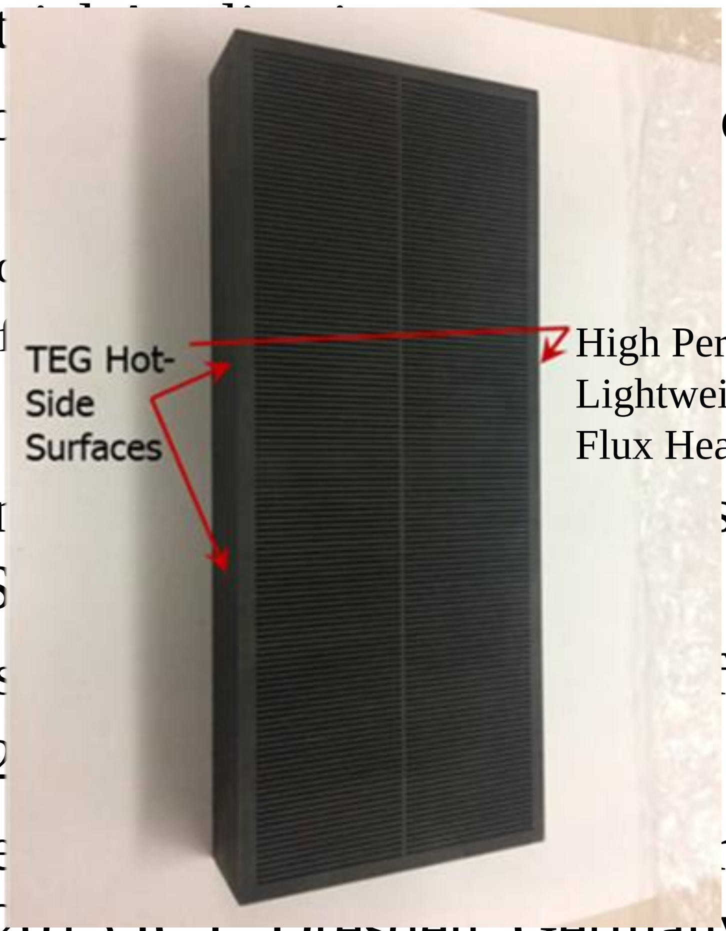
- Project Goals are Often Tied to:
  - Energy Savings
  - Environmental Savings and Impacts
- Critical Peripheral Benefits Also Surface Beyond These Savings
  - Improved Product Quality (PACCAR Kenworth)
  - Improved Safety (Less Indoor Air Pollution)
  - Enhanced Product Throughput Due to Process Efficiency Increases
  - Enhanced Operational Efficiency (Less Water Use)



- Challenges:
  - Scaling Up to Industrial Processing Energy Flows
  - System Cost and Payback
  - Integrating into Industrial Processes Without Adversely Impacting Product Quality and Critical Metrics
  - High-Temperature Materials – Durability and Operational Maintenance
    - $La_{3-x}Te_4$, Zintls, Skutterudite TE Materials are One Solution
  - In Some Cases, Similar Source Temperature and Energy Flow Variability as in Automobile Applications
  - “Occupied” Volume and Compactness
    - JPL Working on Higher Power Density TE Solutions in Automotive and DARPA Programs

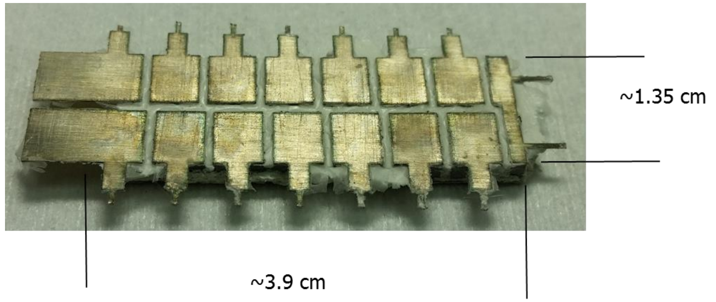
Terrestrial Waste Energy Recovery

- Thermoelectric Systems Considered a Prime Energy Recovery Technology Candidate / Option in Many Terrest
- Terrestrial Energy Reco o:
  - Energy Savings
  - Environmental Savings and
  - Maximizing Conversion Ef
  - Maximum Power Output
- However, JPL is Curren signs Where the Critical Design Metric is Maximizing S
  - Knowing Its Relations ficiency Points is Key
  - T_{exh} = 823 K; T_{amb} = 2
- In Addition, Key Barrie mance Anymore as System-Level Cost (As Discussed in 2015 ICT, Dresden, Germany)



High Performance, Lightweight, High Heat Flux Heat Exchanger

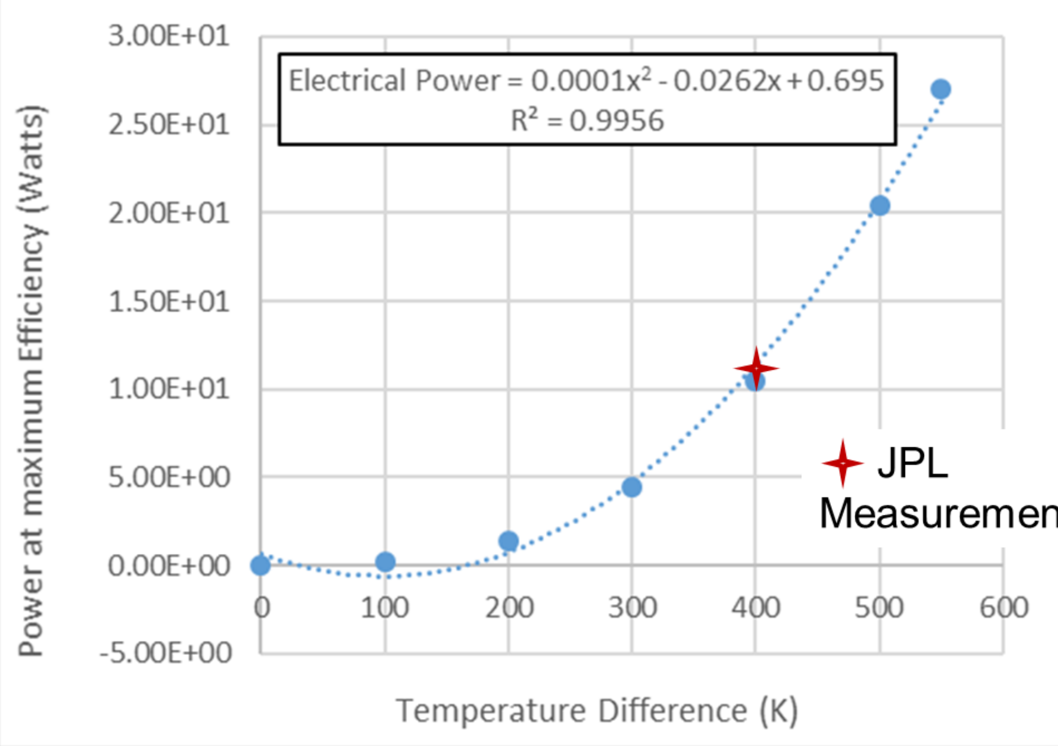
High Performance, High Power Flux Skutterudite TE Module Technology

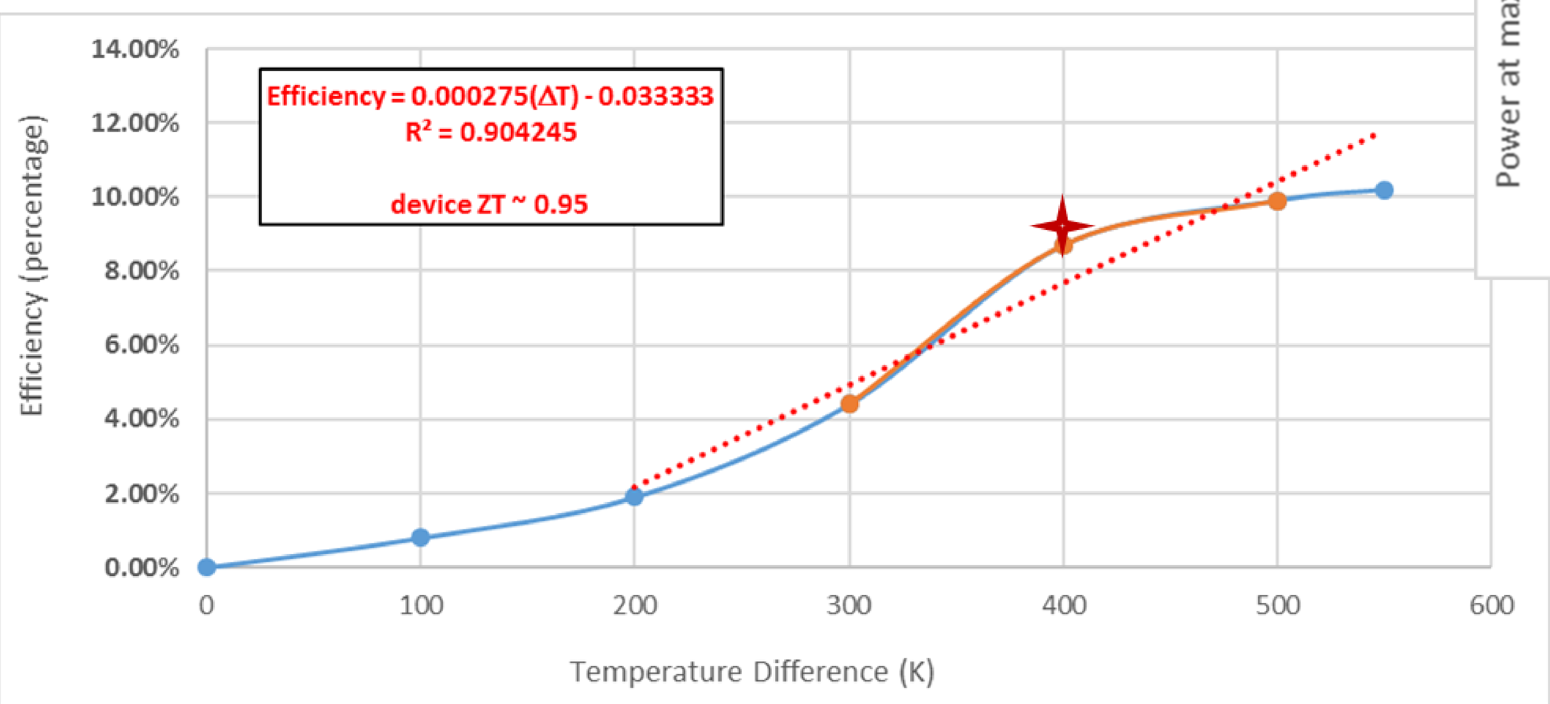


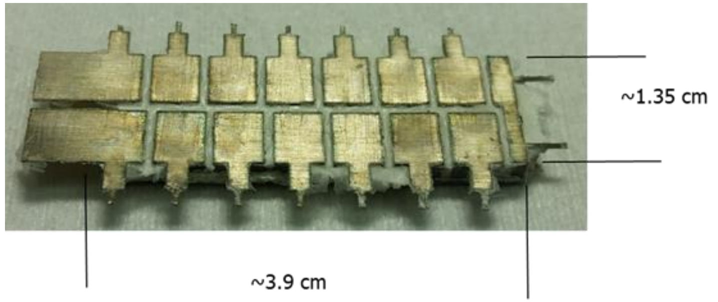
Cost Modeling and Integrating Cost Modeling With System-Level Performance Modeling is Critical

High Power Density TE Module Technology

- All-skutterudite module technology demonstrated
- High efficiency TE module demonstrated
- High Power ➡ High Power Density TE module demonstrated
- Highest power density demonstrated to date
- Exactly what is needed for various terrestrial energy recovery applications



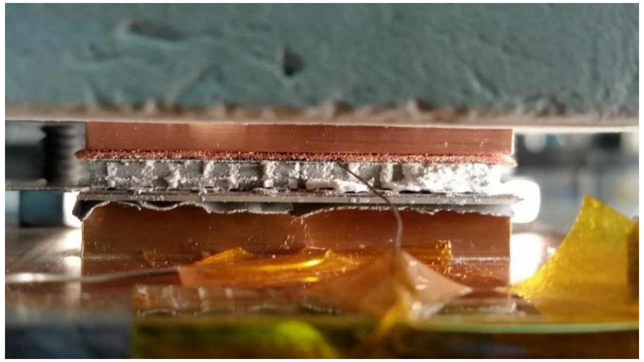




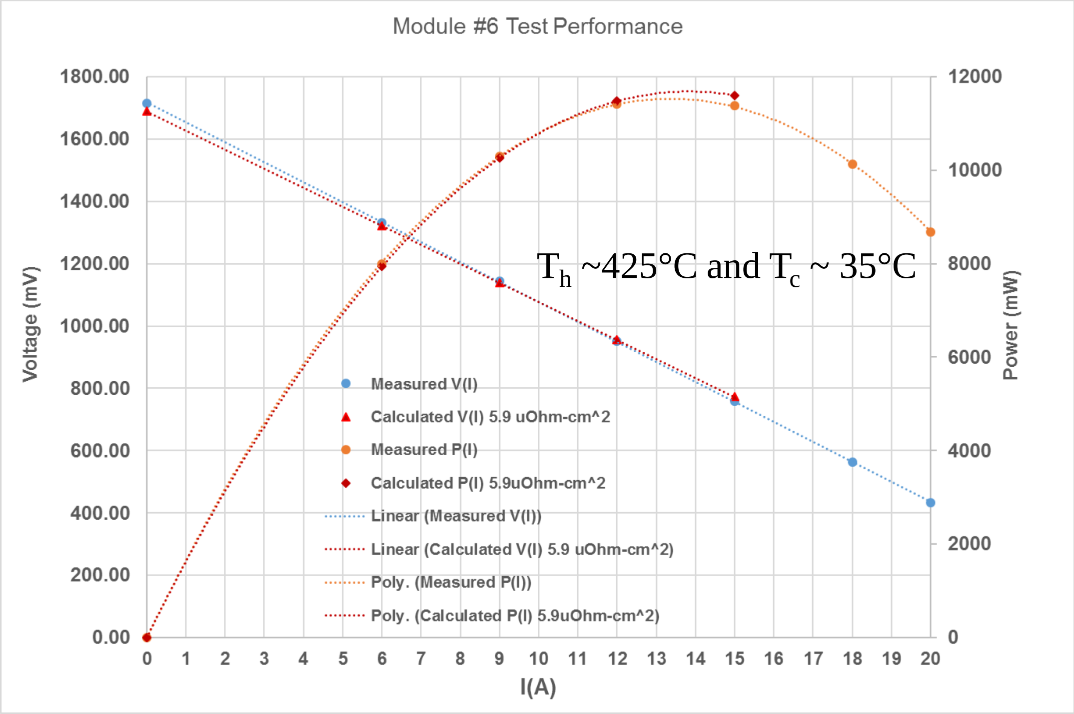
JPL is ready to work with industry to commercialize this technology

TE Module Testing

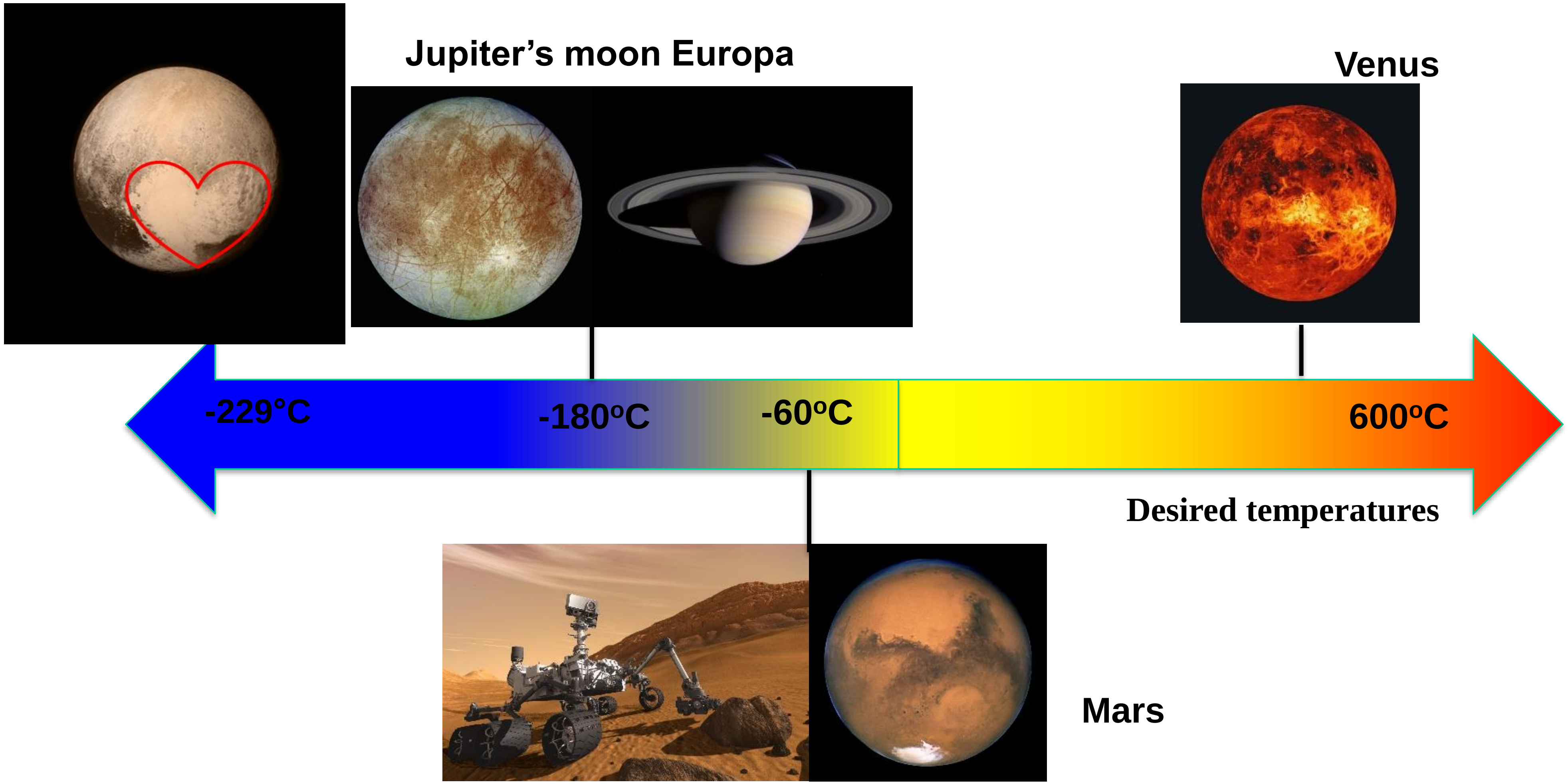
- Latest TE module test data looking better than ever
- Full I-V curve with comparison to model predicts
- Module measured resistance via I-V curve = 64.1 mΩ at temperature - Good compared to expected 60 mΩ
- Power output was 20 W at T_h ~525°C and T_c ~ 20°C
  - Best Ever for JPL All-SKD TE Module
  - Power flux ~ 3.8 W/cm^2 (Module Footprint Area)
  - Power flux ~ 9 W/cm^2 (TE Element Area)
- Thermoelectric efficiency ~10%
- Hot-side thermal resistances have now been analyzed with the aid of specific testing for hot-side ΔT's
- Working to get T_c lower now and lower thermal contact resistances at hot- and cold-sides.
- Even exposed to some thermal cycling – Internal resistances stayed constant



Module Mounted in Test System



Extreme Environments

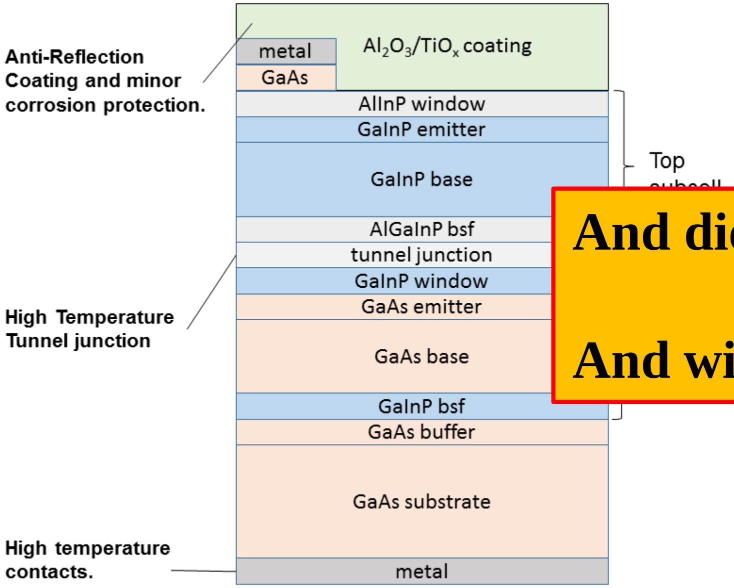


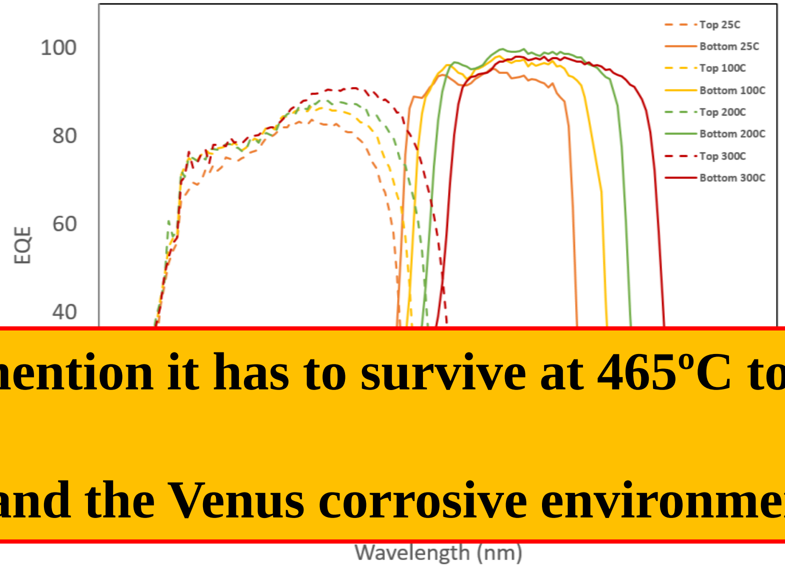
Extreme environmental conditions for planetary missions (e.g., temperatures, gravity, thermal shock, radiation, and chemical attack)

High Temperature Photovoltaics for Venus Atmosphere

Objective: Development of a Low-intensity high-temperature (LIHT) solar cells that can function and operate effectively in the Venus atmosphere (~300ºC and 100-300 W/m² solar irradiance conditions).

Simplified cross-section schematic of a GaInP/GaAs 2J solar cell designed for high temperature operation.



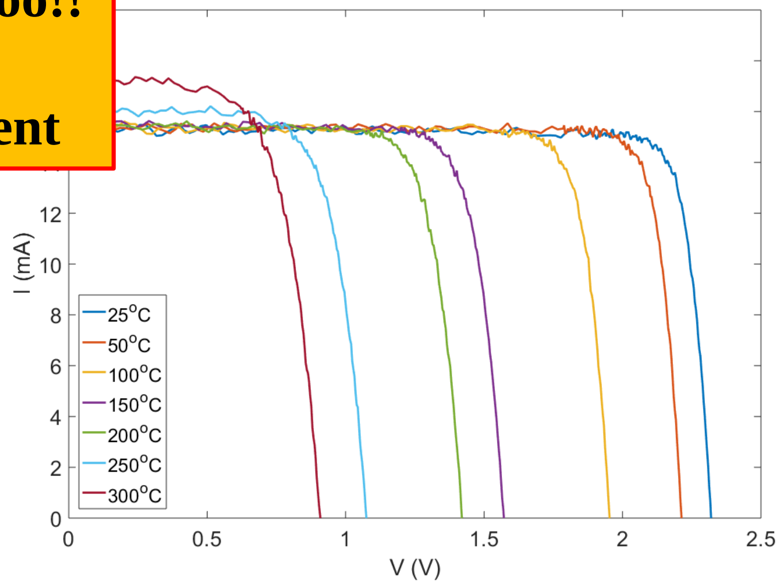


External Quantum Efficiency (EQE) measurement of a solar cell (Top junction and Bottom junction) between room temperature and 300ºC

And did I mention it has to survive at 465ºC too!!

And withstand the Venus corrosive environment

Current-voltage (IV) measurement of a solar l between room temperature and 300ºC



JPL test capability simulates Venus temperature conditions

Solar cell modeling under the atmospheric conditions of Venus used to guide the ideal solar cell structure design – Current density matching of both layers

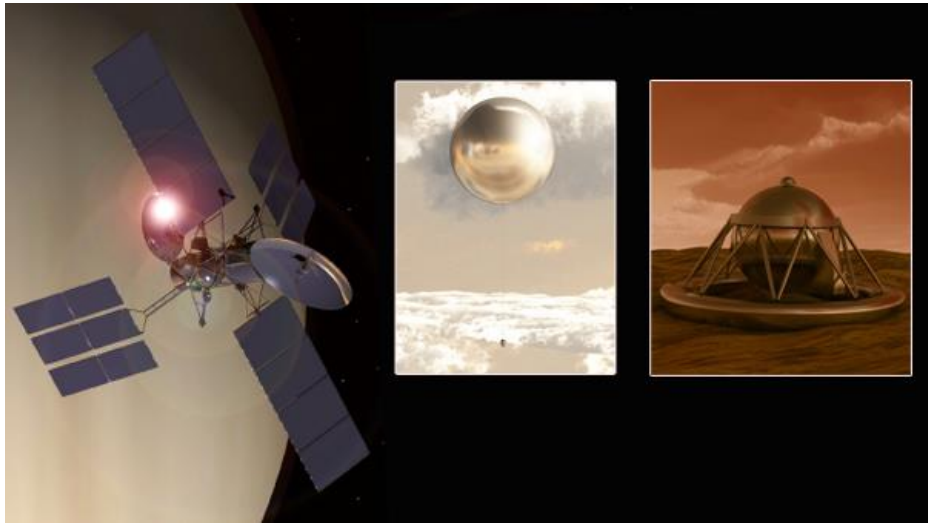
GaInP/GaAs 2J solar cells have initially shown promising performance under high temperature characterization

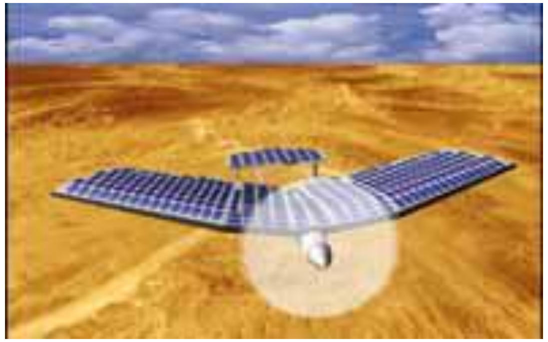
Grandidier et al., (2018) "**Solar Cell Analysis Under Venus Atmosphere Conditions**", 2018 45th Solar Photovoltaic Specialist Conference, Waikoloa, HI. In Preparation

JPL

Potential Missions for Venus Explorations

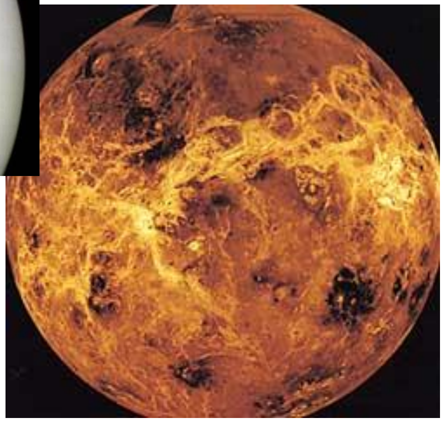
- Extreme environments
  - Not habitable for human
  - Very hot environment (465^{o}C)
  - Sulfuric acid environment
- Venus' high surface temperature overheat solar cells & electronics in spacecraft in a short time
- Potential Venus Missions – Aerial and Surface Missions
  - Venus Design Reference mission
  - Venus Climate Observer (planet C) – Japan Aerospace Exploration Agency (JAXA)
  - Venus Express – European Space Agency (ESA)
- Want to determine what is there
  - Surface Heat Fluxes
  - Strong magnetic fields
  - Possible life in the extremely hot environment?





Examples of Venus aerial and surface mission concepts

Image of the planet taken by the Pioneer Venus Orbiter in 1979



Computer Simulated Global View of Venus

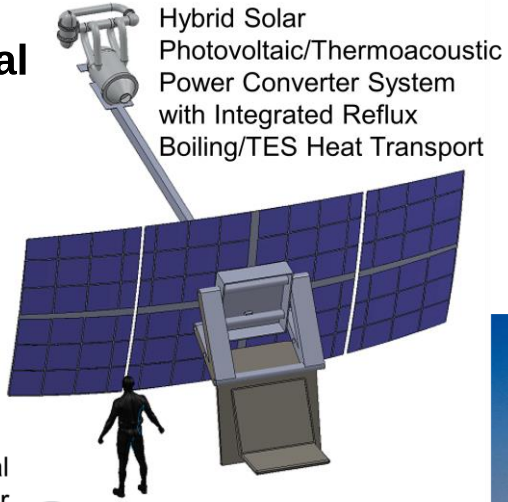
Terrestrial Solar Power Applications for High Temperature PV

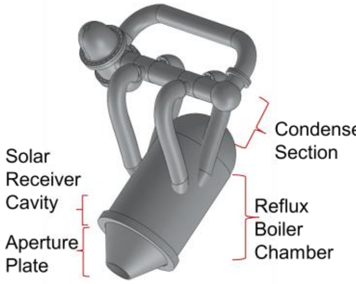
- High Temperature Photovoltaics Can Translate into Power Tower Applications
- Also into Full Spectrum Hybrid Photovoltaics/Thermodynamic Cycle Systems

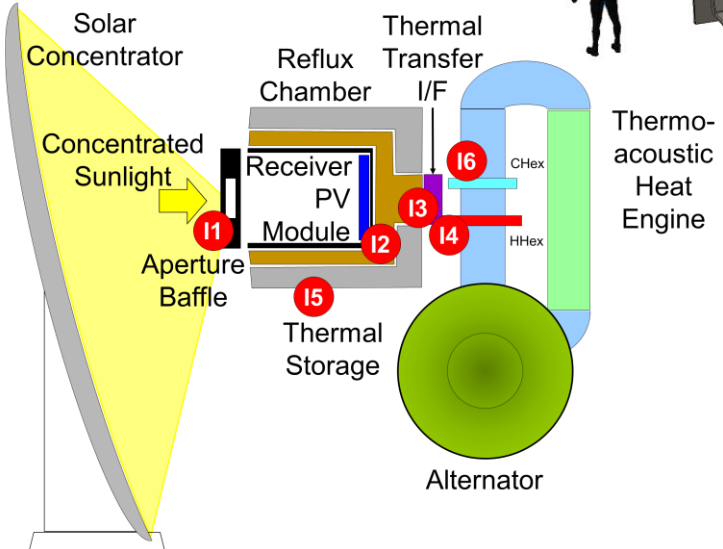
[1] Full Spectrum Hybrid Photovoltaics and Thermal Engine Utilizing High Concentration Solar Energy

[2] Efficient Heat Transfer Methods in a Hybrid Solar Thermal Power System for the FSPOT-X Project

Ivanpah Solar Power Facility







Solucar PS10 Solar Thermal Power Plant

[1] Grandidier et al., PhotoVoltaic Specialist Conference (PVSC) 2016
[2] Lee et al., ASME Power & Energy 2015, 9th International Conference on Energy Sustainability, PowerEnergy2015-49658

https://en.wikipedia.org/wiki/Solar_power_tower

Final Thoughts & Conclusions

- NASA Power System Development Provides Direct Technology Pathway to Terrestrial "Energy Recovery" Power Systems Applications
- Maybe a 10-20 Year Lag – Getting Shorter Every Year
- Terrestrial Power Has Many Similar Requirements as Spacecraft Systems
  - Cost is Always An Issue
  - Space Environments More Extreme Than Terrestrial (Hot - Venus & Cold – Mars & Beyond)
  - Terrestrial Applications Have Severe Cost & Environmental Requirements
    - Spacecraft Power System Materials in Large Quantities in Earth-Based Applications Can Sometimes Cause Severe Issues on Earth
    - System Costs Generally Need to approach \$1-3/W to be Competitive – TE WHR Power System Costs are Often Heat Exchanger Driven
  - JPL's latest advancements in high-power-density TE module technology & high performance heat exchangers to address needs
- Goal is to Transition Terrestrial Technology Advances Back into NASA Missions & Systems
- JPL is Happy to Collaborate with Industry & Academia in Developing These Technologies

Terrestrial Power Advances ⟷ NASA Mission Requirements

Expanding Our Energy & Biosensor Toolbox

Learn from the mistakes of others. You won't live long enough to make them all yourself.

Yogi Berra

Catch This Wave …… And **Ride** It!!

We Can Do This!! We Have the Tools and Knowledge!

This Too Can Be The Ride of Our Lives!!

AN ENERGY TSUNAMI AHEAD

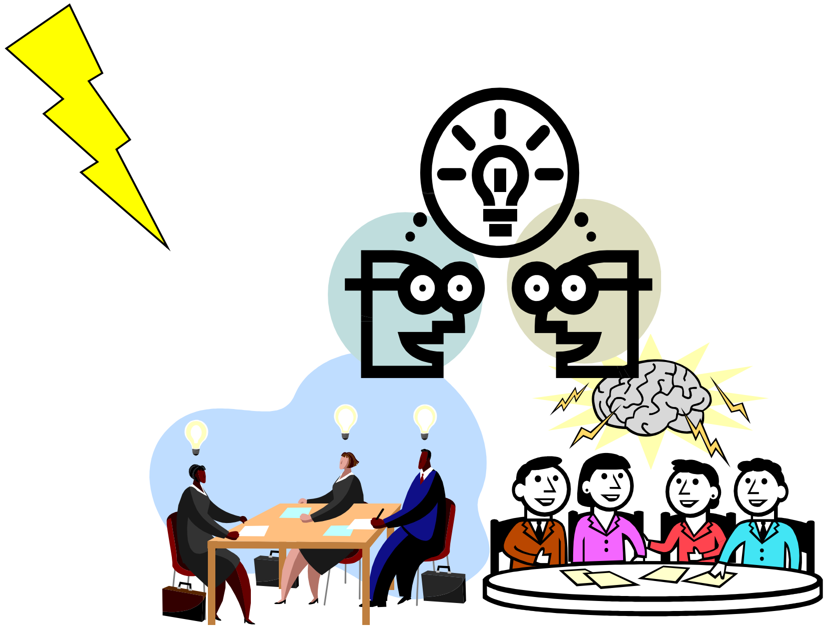
ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract to the National Aeronautics and Space Administration.

Thank you for your interest and attention

Some People See the World as It Is and Ask Why…… I Dream What Has Never Been and Ask Why Not? Robert F. Kennedy, 1968

Questions & Discussion

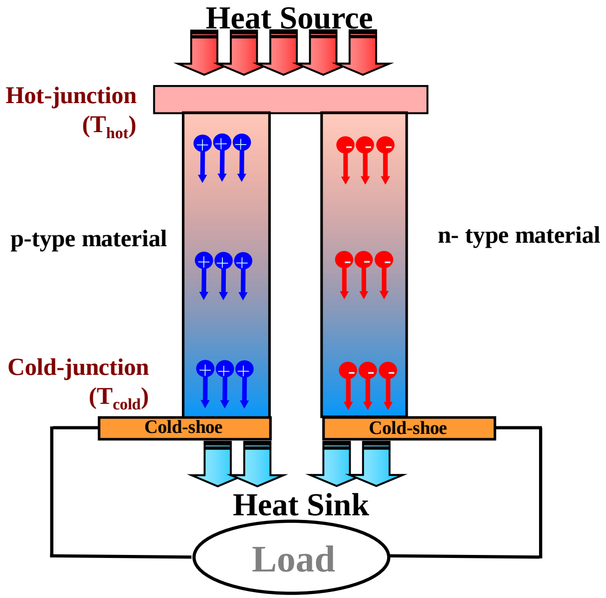


BACKUP SLIDES

* Methane is the world's most abundant hydrocarbon. It's the major component of natural gas and shale gas and, when burned, is an effective fuel. But it's also a major contributor to climate change, with 24 times greater potency as a greenhouse gas than carbon dioxide.

Thermoelectric Power Generation

Thermoelectric Couple

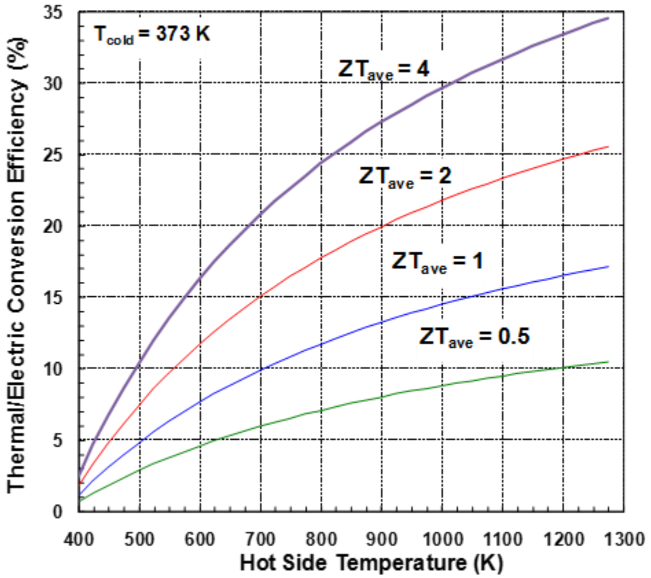


Thermoelectric effects are defined by a coupling between the electrical and thermal currents induced by an electric field and a temperature gradient

Dimensionless Thermoelectric Figure of Merit, ZT

$$ZT = \frac{\sigma S^2 T}{\lambda} = \frac{S^2 T}{\rho \lambda}$$

Seebeck coefficient S
Electrical conductivity σ
Electrical resistivity ρ
Thermal conductivity λ
Absolute temperature T



Conversion Efficiency

Common TE Materials:

Bi_2Te_3 300 K – 525 K
PbTe-based 400 K – 775 K
SiGe-based 525 K – 1273 K
Skutterudites 475 K – 875 K
$La_{3-x}Te_4$/Zintls 625 K – 1273 K

Power generation

(across 1275 to 300 K)
State-Of-Practice materials:
$ZT_{average}$ ~ 0.5

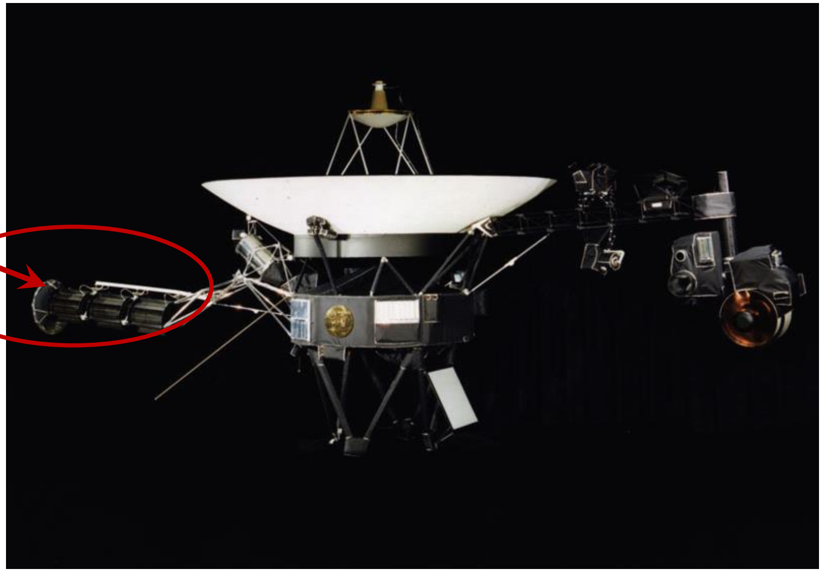
State-Of-the-Art materials:
$ZT_{average}$ ~ 1.1

Best SOA materials:
ZT_{peak} ~ 1.5 to 2.0

Conversion efficiency is a direct function of ZT and ΔT

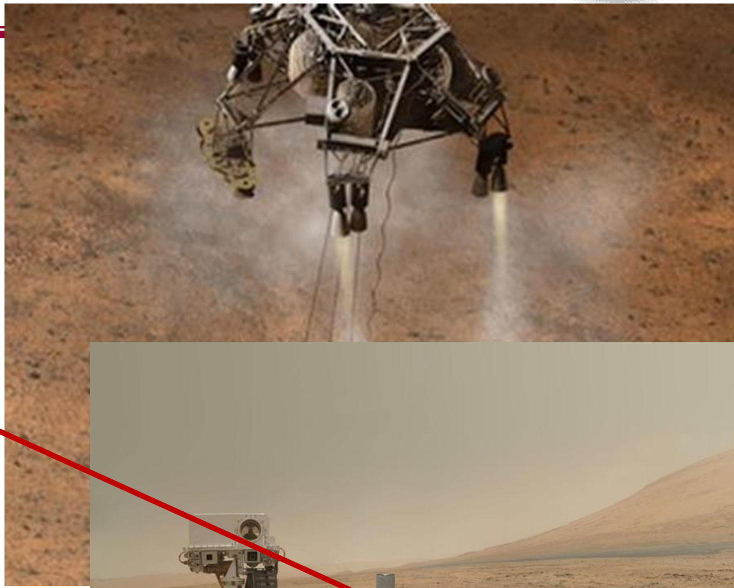
Voyager – Interstellar Mission (1977)

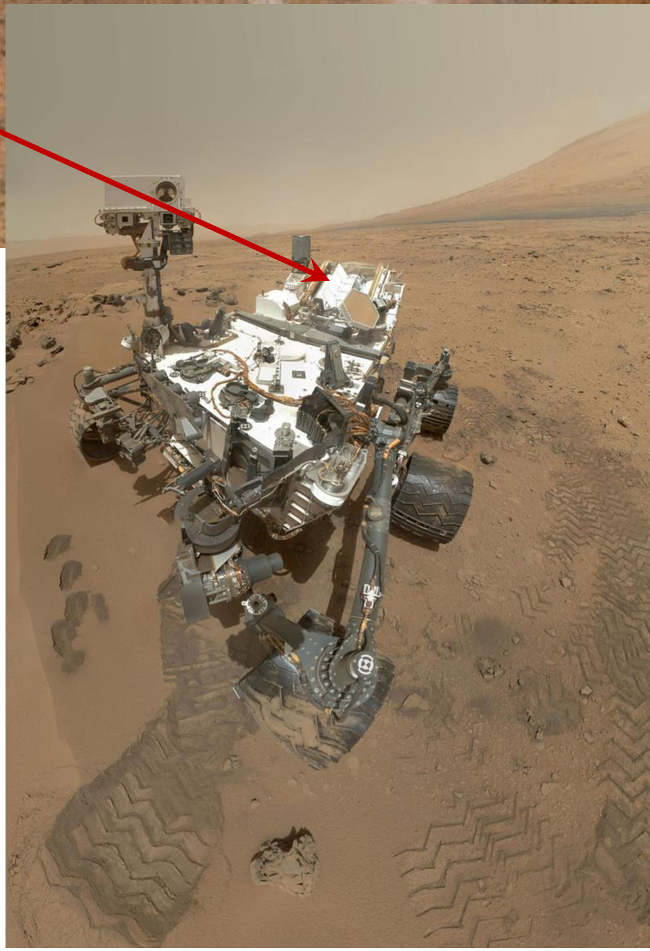
- Launched 37 Years Ago
- Traveled Farther than Anyone, or Anything, in History – 11 billion miles from Earth Now
  - First Spacecraft to Travel Beyond Our "Solar Wind"
- First Flyby Studies of Jupiter, Saturn, Saturn's rings, and the Larger Moons of the Two Planets, Neptune, Uranus
  - Discovered 3 of Jupiter's Moons – Adrastea, Metis, and Thebe
  - Detailed Investigation of Saturn's Rings
- Now in Interstellar Space Outside our Solar System
- RTG Power System (Based on Si-Ge Thermoelectric Materials)
  - Still Operating and Powering Spacecraft



MARS SCIENCE LABORATORY (2012)

- Landed the Curiosity Rover on Mars in 2012 – Sky Crane
- About the Size of a Small Car (~2000 lbs)
- Radioisotope-Driven Thermoelectric Generator (RTG) Used to Power Curiosity
- Spent the Last 2 Years Investigating the Geology on Mars
- 1st Year on Mars - Discovered Strong Evidence of Prior Water on Mars
  - 3.5 Billion Years Ago We Think Mars Had Rivers, Lakes, & “Oceans”
  - Theory – Lost Its Magnetic Field & Atmosphere was Ultimately Destroyed
- Spent Last Year “Driving” from Landing Site to Mt. Sharp
  - 3-mile High Martian Mountain
  - Currently in the Foothills of Mt. Sharp
- Geology on Mars Similar to Earth





RTG Power With Heritage TE Materials Made this All Possible
TAGS, PbSnTe, PbTe TE Materials – Segmented Elements

U.S. National Waste Energy Recovery

- **Transportation Sector**
  - 12.5 Quads
  - Light-Duty Passenger Vehicles + Light-Duty Vans/Trucks (SUVs)[1]
  - Medium & Heavy-Duty Vehicles[1]

- **Industrial Process Sector is Another Opportunity**
  - 5-10 Quads of Waste Energy Flows in Industrial Processes
    - Aluminum, Glass
    - Paper
    - Petroleum
    - Chemical
  - 1.8 Quads Recoverable, Potentially 1.56 GW[2]
  - Wide Range of Temperatures & Heat Sources

- **Europe and Asia Have Similar Challenges**

Waste Energy All Around Us

[1] *Transportation Energy Data Book*, 2010, Edition 29, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicles Technology Program. ORNL-6985, Oak Ridge National Laboratory, Oak Ridge, Tennessee. http://cta.ornl.gov/data/index.shtml.

[2] U.S. Energy Information Agency, 2007 Annual Energy Outlook

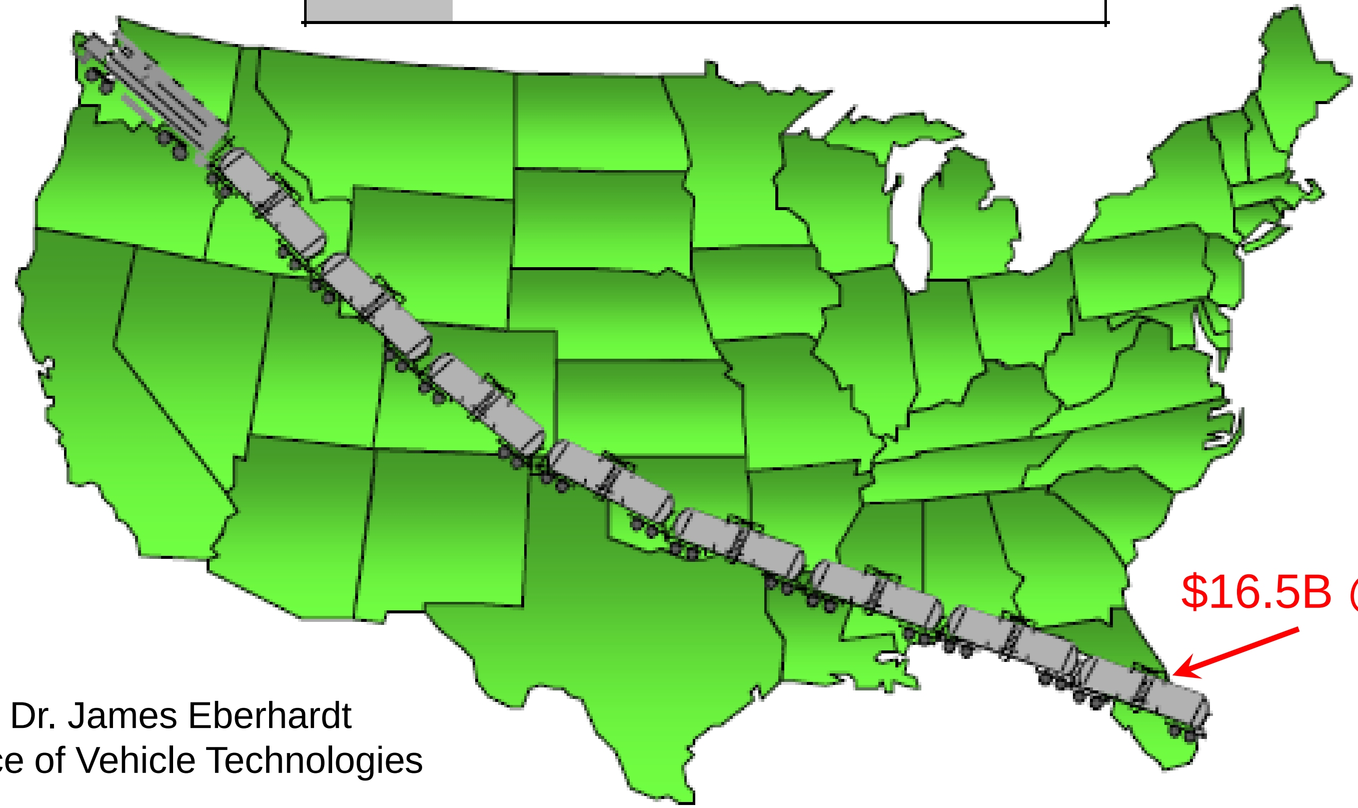
The Magnitude of Our Energy Problem

Office of Heavy Vehicle Technologies

	1973	1997
U.S.	74 Quads	91 Quads
World	225 Quads	365 Quads

2014
~98.3 Quads[1]

[1]U.S. Energy Information Agency



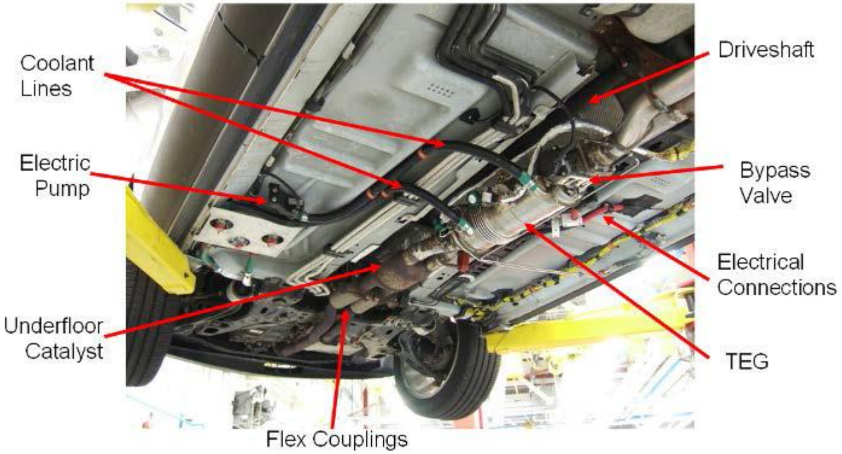
$16.5B @ $50/Barrel

Reference - Dr. James Eberhardt
DOE – Office of Vehicle Technologies

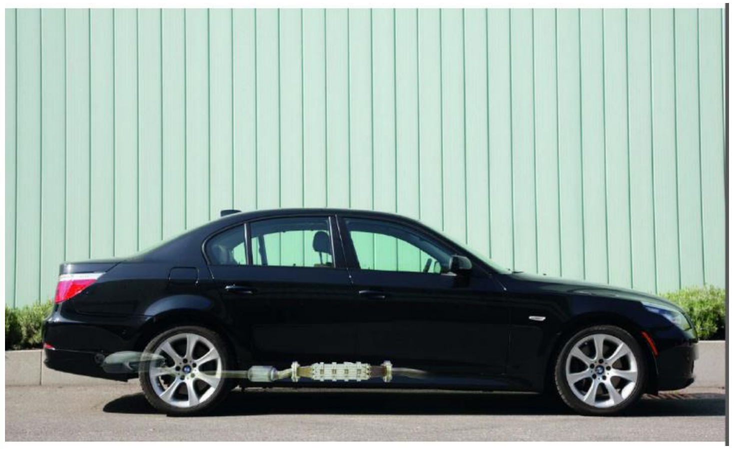
1 Quad of energy is equivalent to 340,000 tank cars of crude oil stretched from Miami to Seattle (3,300 miles).

Thermoelectrics in a Ford Lincoln MKT & BMW Series 6 (May 2012)

- Demonstrated 450 W Power Output on a BMW Drive Cycle at 130 kph
- Demonstrated 300 W Power Output on a Ford Lincoln MKT at 65 mph

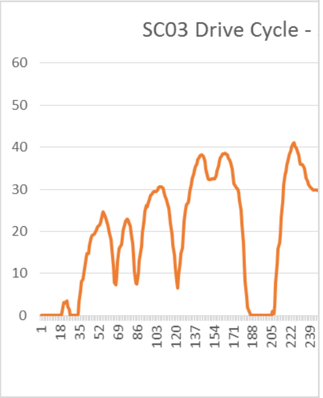


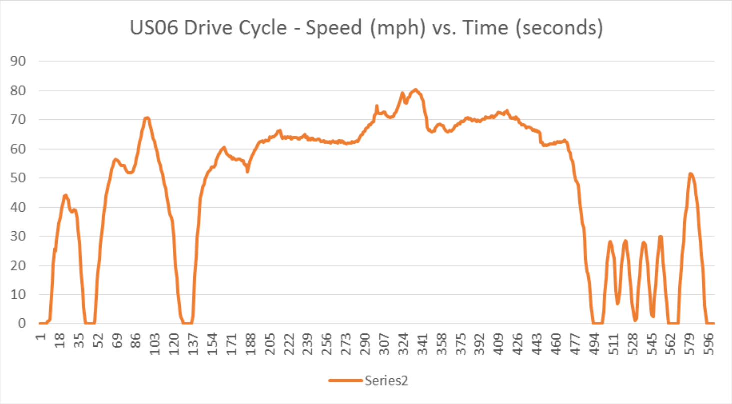
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/adv_combustion/ace080_lagrandeur_2012_o.pdf

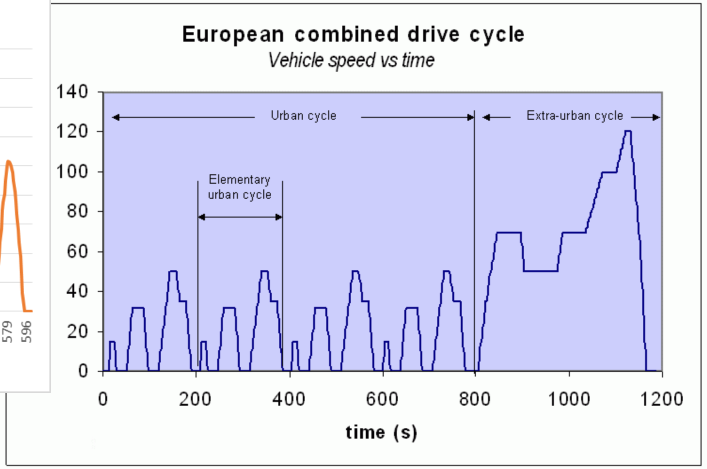


https://www1.eere.energy.gov/vehiclesandfuels/

- BMW ultimately interested in average power over NEDC
- Ford and U.S. Auto Companies ultimately interested in US06 & SC03







Drive cycle contained in UN/ECE Regulation 101

Low-Power Energy Harvesting Systems for Outer Planets Mission Concepts

⇨ **Outer Planets exploration activities**
- Through ice, water, cryogenic liquids, hot gases, high g loads, moderate to high radiation
- Such as for Europa landers, Titan explorers, Comet sample return vehicles…

⇨ **Need for miniaturized robust power sources**
- To enable/prolong planetary exploration, to permit novel/more science measurements
- To enable development of novel miniaturized autonomous probes such as drop-off penetrators, weather microstations, communication relay devices, etc…